ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

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Prepared by:

Bruce Miller
Donald A. Normandeau
Glenn Piehler
Pamela Hall
Arthur Mathieson
Richard Fralick
Donna Turgeon
Philip Mahoney

NORMANDEAU ASSOCIATES, INC.
Manchester, New Hampshire

and

Wadsworth Owen

VAST, Inc.
Hartford, Connecticut

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I. GENERAL INTRODUCTION TO THE STUDY

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

I. GENERAL INTRODUCTION TO THE STUDY

A. THE PROBLEM:

Population is growing at a steady rate throughout the already crowded northeast, and with this increase comes the critical problem of how to best plan for and provide the basic services needed to improve or at least sustain the present standard of living. Of all the crises facing the region, water shortage may be one of the more critical, for water resources now existent in the vicinity of eastern Massachusetts will not be sufficient to meet the needs of the population projected for the next twenty years. This problem can be solved by reducing the overall demand for water by limiting the population to the natural carrying capacity of the watershed area, by reduction of per capita consumption, or by diverting water from adjacent watersheds to augment the existing supply. In the immediate absence of an acceptable method of population limitation or per capita consumption reduction, water may have to be diverted to meet the projected demand.

The North Atlantic Division of the Army Corps of Engineers has the responsibility of alleviating water needs in this region, and to fulfill this responsibility the Corps has considered three plans to augment the existing water supply. One plan, initiating a diversion of water from the Connecticut River into Quabbin Reservoir in Massachusetts, has already been accepted by the Commonwealth of Massachusetts. The second, the Tully diversion, is in the initial planning stage, and a third plan, still in the formative stage, involves a diversion of water from the Merrimack River. The Merrimack River Estuary Ecological Study has been designed to determine the potential environmental effects of diversion of water from the river in the vicinity of Lowell, Massachusetts, and to give a qualitative evaluation of the significance of these effects to the ecology of the estuary and associated wetlands.

Relatively little work has previously been done on the ecology of the estuary, and the present study, of less than nine months duration, has only covered limited aspects of the estuarine environment. Implicit in a study of this scope and duration is the understanding that quantitative data are not available, and definitive answers cannot be presented at its conclusion. However, the study will serve to clarify many aspects of the existing ecology of the estuary, and will point out the potential areas of change that a diversion may impose upon the estuarine environment. If the diversion appears to be feasible, the questions of critical concern will necessarily have to be studied in further detail before the plan can be implemented.

B. SCOPE OF THE PROJECT

The Merrimack River Estuary Ecological Study has been designed to determine whether diversion of Merrimack River water from the vicinity of Lowell, Massachusetts, to the Eastern Massachusetts region for water supply purposes would significantly alter the ecological, biological, and physical characteristics of the Merrimack River Estuary. This determination has been made on the basis of field investigations, existing literature, and other available information, and has been supported by an analysis of the effects of simulated flow diversions upon the historic period of record.

The diversions are being considered from two viewpoints. First, a direct diversion of flow from the river utilizing "natural" flows. The wide range of diversion rates that has been selected is intended to gather the widest information band possible with respect to potential diversions. None of the flow rates have been selected nor is it anticipated that higher rates would, in fact, be adopted.

The following diversion rates (100, 300, 500, 800, 1,100, 1,500, and 2,000 cfs) were evaluated for their possible effects on the estuary, when the average daily flows, as measured at the U. S. Geological Survey gauging station at Lowell on the Merrimack River, exceed the following control flows:*

October-May	800 cfs
June	1,000 cfs
July	1,500 cfs
August	1,500 cfs
September	1,000 cfs

*Diversions will not cause river flows to be less than the control flows.

Secondly, diversions were evaluated with a provision for upstream storage and flow augmentation release during low flow periods. The effect of this storage is reflected in the analysis primarily during the spring and summer periods. During the spring period only (March, April, and May) the diversion rates given in the preceding section are increased as follows:

185 (vs. 100)	2,850 (vs. 1,100)
610 (vs. 300)	5,170 (vs. 1,500)
1,070 (vs. 500)	8,050 (vs. 2,000)
1,860 (vs. 800)	

During low flow periods this storage would be released to "make up" the difference between desired withdrawals, control flow, and natural flows conditions. Thus, no effect would be recorded on salinity beyond the spring period.

The study was composed of two major parts. The first pertains to possible physical changes in the estuary, primarily salinity, brought about by diversion. The second relates to the biotic communities, permanent and temporary, occurring in the estuary, and the potential effects the diversion might have upon them.

A mathematical model to graphically represent the longitudinal salinity distributions predicted for each incremental change in freshwater flow of the Merrimack River throughout the year was generated by Vast, Inc. of Hartford, Connecticut. Data used in the preparation of this model consisted of existing data on salinity and river flow, augmented with data collected from April through September, 1971 by Normandeau Associates at the Merrimack River stations established by Jerome, et al (1965), and three additional stations located upriver. This description includes an analysis of the present and projected salinities at the eight sampling stations. In addition to the salinity data collected for inclusion into the mathematical model, additional salinity readings have been collected by Normandeau Associates throughout the sampling period.

Potential effects of physico-chemical changes other than salinity have also been considered, including changes in the pattern of sedimentation, alterations of current flow, reduction in temperature extremes, changes in transparency, pollution load, and BOD.

The evaluation of physico-chemical changes related to diversion, along with the results of a series of biological samplings taken throughout the study period, have been used to explore the potential effects of freshwater diversion on the biology and ecology of the estuary. Throughout the project period, studies have been conducted at 39 sampling stations to determine the existing distribution and relative abundance of six major groups of organisms along the length of the tidal estuary (i.e., intertidal benthos, subtidal benthos, plankton, finfish, intertidal algae, and intertidal vascular plants). The results of these studies have been utilized in an attempt to answer the following questions:

1. What is the existing distribution of species? Are these species marine, estuarine or freshwater?

2. What are the dominant species in the biological association at each station?

3. What part of the life cycle of each species will be most affected by the potential physico-chemical changes? At what time of the year is this situation most critical?

4. How will the biological association change with potential physico-chemical changes?

5. Will the change in the biological association at each station lead to other biological or physical changes?

6. Will new species be introduced at some stations with changes in physico-chemical factors? Will some species be eliminated?

7. What will be the net effect of potential physico-chemical changes on the ecology of the Merrimack River Estuary?

In conclusion, an attempt has been made to determine the effects that are potentially of greatest significance to the overall stability of the estuarine environment, and approaches are suggested to study these effects in greater detail if the diversion plan is to be pursued further.

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II. DESCRIPTION OF THE STUDY AREA

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The Merrimack River is one of the five largest in New England, draining an area of approximately 12,970 Km^2.* The river has its source in the New Hampshire White Mountains, and flows in a generally southerly direction to the sea in northeastern Massachusetts. A considerable portion of the river is subject to tidal action, and measureable salt intrusion periodically occurs more than ten miles from the sea. For the purpose of the present report, the estuarine study area includes those portions of the tidal river presently or potentially exposed to measureable salt intrusion (Figure 1).

The channel of the estuary is continually scoured by tidal currents and the sediment is coarse, whereas shallow intertidal areas are covered by fine mud, silt, and sludge from domestic and industrial pollution and natural siltation. Some rock outcroppings are present along the length of the estuary, but for the most part the region is characterized by extensive salt marshland nearest to the ocean, and low deciduous and pine forest further upriver.

A complete description of the hydrography of the Merrimack River Estuary, along with a list of references pertinent to the area, was pub-

*1 Km = 0.621 mile

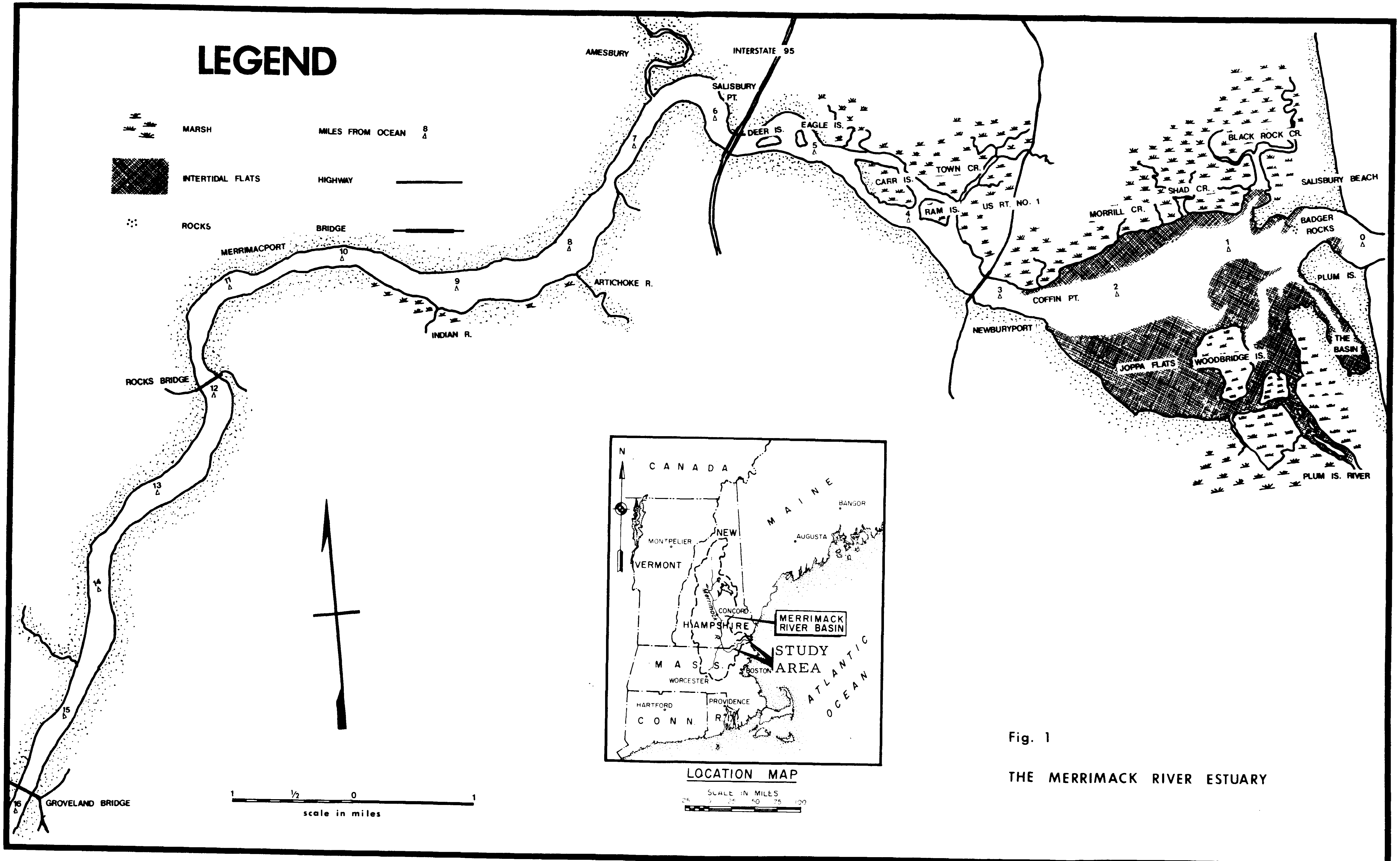

Fig. 1

THE MERRIMACK RIVER ESTUARY

lished by Hartwell (1970), and a detailed analysis of the marine resources of the region was written by Jerome, *et al* (1965).

ECOLOGICAL STUDY

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III. SALINITY STUDY, MERRIMACK RIVER ESTUARY

MATHEMATICAL MODEL

III. SALINITY STUDY, MERRIMACK RIVER ESTUARY

MATHEMATICAL MODEL

A. INTRODUCTION AND OBJECTIVES

The objective of the Ecological Study of the Merrimack River Estuary is to determine if diversion of river water before it enters the estuarine section of the river basin would significantly change the physical or ecological character of the estuary.

Normandeau Associates, Inc., an ecological consulting firm, was given the overall responsibility for the performance of the ecological survey. VAST, Incorporated, under subcontract to Normandeau Associates, was given the task of developing a one-dimensional mathematical model of the Merrimack Estuary to determine the effects of various amounts of diversion on the salinity characteristics of the estuary.

An estuary may be defined as a semi-enclosed coastal body of water in which sea water is diluted by freshwater runoff from the land (Pritchard, 1959). Estuaries are usually subject to tidal action which is often the most readily apparent water motion. More subtle in nature and yet in many ways more important is the net non-tidal circulation brought about by pressure forces set up by the variations in density due to dilution of sea water by the less dense freshwater runoff from the land. This circulation governs and establishes the flushing characteristics of the estuary and together with other factors the limit of saltwater intrusion in the estuary. The saltwater intrusion limits are of major importance to the ecology of the Merrimack and give rise to the need for the mathematical model.

The mathematical model used in this study is based on the salt balance equation of Pritchard (1959) in which the seaward salt advection is balanced by turbulent diffusion toward the head of the river. Data from actual measurements made by previous researchers on the river and also by Normandeau Associates have been used to determine the diffusion coefficients and boundary conditions for the partial differential equation used in the model. Once these coefficients and boundary conditions are determined the equation can be used to predict the effects of future diversions on the salinity and on the limit of salt intrusion which is important to the ecology of the Merrimack River. Thus the results of the VAST mathematical model study will provide information necessary for the ecologists to assess the ecological impact of diversion on the Merrimack River Estuary.

B. APPROACH

The approach used in this study of the salinity of the Merrimack River Estuary has been to clearly state the problem, evaluate the possible methods of solution of the stated problem, select the method most consistent with the available data to solve the problem, and to devise an efficient method, in terms of user time, of presenting the solution.

1. Problem Statement

The problem to be solved is: Generate a mathematical model to describe the effects of proposed diversion of freshwater from the Merrimack River Basin on the limit of saltwater intrusion and on the salinity of fixed stations in the Merrimack.

2. Review of Applicable Models

The most elementary model of an estuary is an embayment in which complete, instantaneous mixing is assumed for each tidal cycle. This model may have some elementary application for bar-built estuaries, however, its greatest value is in its conceptual use in the development of more realistic models such as the segmented model. The next step in increasing complexity and realism is the segmented model in which each segment is completely mixed, conservation equations are used and exchange factors are developed for each segment. In this type of model Ketchum (1950) has taken the extent of the tidal excursion for the length of the segments.

Dorrestein (1960) developed a model for the Ems estuary in which he considered the exchange coefficients to be functions only of the position within the estuary, and apparently obtained good agreement between predicted and observed values of tracer concentration for a given river flow. Another example of a segmented model is Thomann's which Hetling (1968) applied to the Potomac Estuary. Using observed boundary conditions and diffusion coefficients determined empirically, partly from observed salinity distributions and partly from dye studies, Hetling used the model to study the effect of increased diversion of freshwater to supply the Washington, D. C. metropolitan region.

An approach that presents an attractive alternative to the segmented box model involves the direct use of a one-dimensional form of the salt balance equation. Pritchard (1959) numerically integrated a time-dependent, one-dimensional salt balance equation in application to the Delaware Estuary. The diffusion coefficients were determined from measurements made on the Delaware hydraulic model at Vicksburg, Mississippi, and boundary conditions were fixed at both ends of the estuary. Boicourt (1969) added a time varying boundary condition to Pritchard's model and applied it to the Upper Chesapeake Bay. Boicourt was able to predict the salinity distribution in the Upper Chesapeake Bay for a given freshwater inflow from the Susquehanna River. Boicourt used one year's salinity data to determine the functional dependence of the coefficient on the freshwater inflow. The boundary value at the head of the estuary was held fixed, while the seaward boundary value was allowed to vary with time. A separate predictor model related this value to the flow of the Susquehanna.

3. Model Selection

After a detailed review of the available models, a model based on the salt balance equation of Pritchard (1959) was selected for the Merrimack River Study. A time varying boundary conditions was added to the model following the method of Boicourt (1969). This model is the most realistic (and complex) that is compatible with the available data. A more complex model would require much more detailed measurement in time and in space. In our opinion, the additional cost in both time and money to obtain the additional data and to implement a more complex model would not be justified for the present purpose. The particular model had also been used to test the effects of diversion of water from the Susquehanna Basin through the Delaware Canal with measurable success, providing further confidence for this approach. Further, it appeared that the frontal salinity distribution in the Upper Chesapeake Bay is similar in many respects to the frontal salinity distribution in the Merrimack Estuary. Thus, it appeared that the longitudinal advection and the turbulent diffusion terms on which the salt balance equation is based would have a similar importance in the Merrimack, as in the Upper Chesapeake Bay. In the Upper Chesapeake Bay the variation of cross-section area with the tide is not great and the assumption is made that the cross-section area does not change as a function of the tide. However, it is not possible to make this assumption in the

Merrimack where the range of the tides measurably affects the cross-section area. To solve this problem the model of the Merrimack is actually two models, one for high tide and one for low tide. In summary, the salt balance equation of Pritchard in modified form as discussed above was selected for the Merrimack River Study because it appears to be the most realistic model compatible with the available input data.

C. DESCRIPTION OF THE MODEL AND THE METHOD OF SOLUTION

In modeling geophysical phenomena, one is usually faced with two practical restrictions on the detail and the complexity of the describing equations. The first requirement is that the model be mathematically tractable. The second is that the equations use and predict information that relates to available observational data.

A common method for simplifying the equations used in describing an estuary is to integrate in the direction of least variation in tracer property or in the direction in which the variation is of least interest.

The direction of most importance in the Merrimack is the longitudinal direction since this is the direction of the salt intrusion. Therefore, the longitudinal axis was selected for this one dimensional model based on the salt continuity equation in which the seaward salt advection is balanced by turbulent diffusion toward the head of the estuary. Since the interest is in the effects of net non-tidal circulation, the governing equation has been averaged over the tidal cycle. In final form, it is a linear, parabolic partial differential equation with variable coefficients.

1. Derivation

The basic three-dimensional salt balance equation states that the local (Eulerian) time rate of change of salinity is a result of advective transport and diffusion processes:

$$\frac{\partial \overset{*}{s}}{\partial t} = \frac{\partial (\overset{*}{u}\overset{*}{s})}{\partial x} - \frac{\partial (\overset{*}{v}\overset{*}{s})}{\partial y} - \frac{\partial (\overset{*}{w}\overset{*}{s})}{\partial z} + D\Delta^2 \overset{*}{s} \qquad [1]$$

where $\overset{*}{s}$ $\equiv$ salinity at (x, y, z, t),

$\overset{*}{u}, \overset{*}{v}, \overset{*}{w}$ $\equiv$ cartesian components of velocity, and

D $\equiv$ molecular diffusion coefficient for salt.

In dealing with an estuary, one can seldom obtain instantaneous measurement of the variables in equation [1]. Existing measurement schemes usually force the use of some averaged form, in which the molecular diffusion terms are negligible in comparison to eddy diffusion terms that appear as a result of the averaging. Pritchard (1968) has shown that averaging equation [1] over a time scale Δt which is long compared to the characteristic time of molecular motion but small in comparison to the characteristic time of large advective processes such as the tidal period, produces a relation that is more amenable to existing measurement and analytic techniques. If the instantaneous variables are expressed as the sum of a mean value and a deviation term,

$$\overset{*}{s} = s + s' ,$$

$$\overset{*}{u} = u + u' ,$$

$$\overset{*}{v} = v + v' ,$$

and

$$\overset{*}{w} = w + w' ,$$

where as for any variable f

$$f = \langle \overset{*}{f} \rangle_{\Delta t} = \frac{1}{\Delta t} \int_{\Delta t} \overset{*}{f} dt' \quad \text{and} \quad \langle f' \rangle_{\Delta t} = 0,$$

the substituting into equation [1] and using Reynolds' rules for averages, results in

$$\frac{\partial s}{\partial t} = - \frac{\partial (us)}{\partial x} - \frac{\partial (vs)}{\partial y} - \frac{\partial (ws)}{\partial z} - \frac{\partial \langle u's' \rangle_{\Delta t}}{\partial x} - \frac{\partial \langle v's' \rangle_{\Delta t}}{\partial y} - \frac{\partial \langle w's' \rangle_{\Delta t}}{\partial z} \qquad [2]$$

the turbulent fluxes in [2] have conventionally been represented as a product of a diffusivity and a gradient of the mean salinity:

$$K_x \frac{\partial s}{\partial x} \equiv - \langle u's' \rangle_{\Delta t} ,$$

$$K_y \frac{\partial s}{\partial y} \equiv - \langle v's' \rangle_{\Delta t} ,$$

and

$$K_z \frac{\partial s}{\partial z} \equiv - \langle w's' \rangle_{\Delta t} .$$

Based on an analogy to the molecular diffusion case, these coefficients are the nonadvective salt fluxes due to that part of the motion which takes place at time scales smaller than Δt. The three-dimensional salt balance equation now becomes

$$\frac{\partial s}{\partial t} = -\frac{\partial (us)}{\partial x} - \frac{\partial (vs)}{\partial y} - \frac{\partial (ws)}{\partial z} + \frac{\partial}{\partial x}\left(K_x \frac{\partial s}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial s}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial s}{\partial z}\right). \qquad [3]$$

To reduce [3] to a one-dimensional form, a spatial average must be taken over the cross-sectional area of the estuary, σ. The procedure used is similar to that employed in obtaining the time-averaged equations; that is, each of the variables is separated into a spatial average term and a deviation term:

$$s \equiv s_\sigma + s_\sigma' \; ,$$

$$u \equiv u_\sigma + u_\sigma' \; ,$$

$$v \equiv v_\sigma + v_\sigma' \; ,$$

and

$$w \equiv w_\sigma + w_\sigma' \; ,$$

where

$$f_\sigma \equiv \langle f \rangle_\sigma = \frac{1}{\sigma} \iint_\sigma f d\sigma'$$

and $\langle f_\sigma' \rangle_\sigma = 0$.

When these substitutions are introduced into [3] and the equation integrated over the cross section σ, the result is

$$\frac{\partial(\sigma s_\sigma)}{\partial t} = - \frac{\partial(\sigma u_\sigma s_\sigma)}{\partial x} - \frac{\partial}{\partial x} (\sigma \langle\langle u's'\rangle_{\Delta t} + u_\sigma ' s_\sigma '\rangle_\sigma) \quad . \qquad [4]$$

A coefficient $K_{x,\sigma}$ can be formally defined in a similar manner to the turbulent diffusion coefficients in [3]:

$$K_{x,} \frac{\partial s_\sigma}{\partial x} \equiv - \langle\langle u's'\rangle_{\Delta t} + u_\sigma ' s_\sigma '\rangle_\sigma \ .$$

The one-dimensional equation then becomes

$$\frac{\partial(\sigma s_\sigma)}{\partial t} = - \frac{\partial(\sigma u_\sigma s_\sigma)}{\partial x} + \frac{\partial}{\partial} (\sigma K_{x,\sigma} \frac{\partial s_\sigma}{\partial x}) \quad . \qquad [5]$$

The coefficients in the three-dimensional equation can be spoken of as representing nonadvective fluxes over the averaging period which are due to deviation terms that relate to the turbulent flow. Equation [5] balances the mean longitudinal advection with an effective one-dimensional diffusion. The reason for the introduction of $K_{x,\sigma}$ is that it allows one to relate the effective diffusion term to external parameters of the estuary more readily than do the averaged cross-products of the deviation terms. With averaging, continuity considerations allow the replacement of the quantity σu_σ in the advective term by R, the net freshwater inflow to the estuary above section σ. Equation [5] then becomes

$$\frac{\partial(\sigma s)}{\partial t} = - \frac{\partial(Rs)}{\partial x} + \frac{\partial}{\partial x} (\sigma K_{X,\sigma} \frac{\partial s}{\partial x}) \qquad [6]$$

where $R = R(x,t)$ and $s \equiv s_\sigma$.

For practical application of [6] to the estuary, the salinity s has been interpreted as the value of position x at a specified phase of the tide such as slack water before flood, rather than as a true average over the tidal cycle. Under the assumption that the tide simply advects a fixed salinity pattern, these two values should be equivalent.

2. Finite Difference Form

Equation [6] has been used as a model to relate the observed longitudinal distribution to the freshwater inflow. The one-dimensional salt balance equation is linear, second-order, and parabolic, with variable coefficients which are functions of both space and time. In its solution, the property of linearity makes it amenable to numerical finite difference techniques.

The partial differential equation [6] may be converted to a finite difference equation by expanding the derivatives into differences. The time derivative is replaced by a forward difference:

$$\frac{\partial s}{\partial t} \sim \frac{s(t+\Delta t) - s(t)}{\Delta t} .$$

The advective term, involving two variables R and s, is replaced by a central difference:

$$\frac{\partial (Rs)}{\partial x} \sim \frac{R(x+\Delta x)s(x+\Delta x) - R(x-\Delta x)s(x-\Delta x)}{2\Delta x} .$$

The diffusion term can be expressed as

$$\frac{\partial}{\partial x} \left(\sigma K \frac{\partial s}{\partial x}\right) = \sigma K \frac{\partial^2 s}{\partial x^2} + \frac{\partial \sigma K}{\partial x} \frac{\partial s}{\partial x} \quad . \qquad [7]$$

In finite difference form, the first term on the right side of [7] is replaced by a second difference form:

$$\sigma K \frac{\partial^2 s}{\partial x^2} \sim \frac{\sigma K(x)}{2\Delta x^2} \left[s(x+\Delta x) - 2s(x) + s(x-\Delta x)\right] \quad .$$

The second term is represented as follows:

$$\frac{\partial(\sigma k)}{\partial x} \frac{\partial s}{\partial x} \sim \frac{1}{2\Delta x^2} \left\{ \sigma K(x+\Delta x)\left[s(x+\Delta x) - s(x)\right] - \sigma K(x-\Delta x) \left[s(x)-s(x-\Delta x)\right] \right\}$$

When these differences are combined in the salt balance equation there is a choice of whether to take the spatial derivatives at time t or at time t + Δt. The choice of taking the derivatives at t would be attractive because, once s(t) is known, s(t + Δt) can be solved for explicitly, without having to invert a matrix of simultaneous equations. Unfortunately, for the $\Delta t(6.048 \times 10^5 s)$ and Δx(500 m) which were used in the analysis, this differencing scheme would violate the stability requirement for the convergence of the solution. By using an implicit scheme, taking the spatial directives at t + Δt, one has to solve a system of simultaneous equations, but the solution is unconditionally stable. This differencing scheme converts the partial differential equation to a set of difference equations:

$$P_L(x)s'(x-\Delta x) + s'(x) + P_R(x)s'(x+\Delta x) = \frac{s(x)}{P_L(x)} \qquad [8]$$

where

$$P_C(x) = 1 + D(x)[\sigma K(x-\Delta x) + 2\sigma K(x) + k\ (x+\Delta x)]$$

$$P_L(x) = \frac{-B(x)R(x-\Delta x) - D(x)[\sigma K(x-\Delta x) + \sigma K(x)]}{P_C(x)}$$

$$P_R(x) = \frac{B(x)R(x+\Delta x) - D(x)[\sigma K(x) + \sigma K(x+\Delta x)]}{P_C(x)}$$

and

$$B(x) = \frac{\Delta t}{2\sigma(x)\Delta x}, \qquad D(x) = \frac{B(x)}{\Delta x}$$

and s' = salinity at time $t + \Delta t$.

Given an initial salinity distribution in an estuary of length $N\Delta x$, the set of equations [8] can be used in conjunction with the two boundary conditions $S'(0)$ and $S'(N)$ to describe the salinity distribution for a time Δt later.

3. Diffusion Coefficients

The diffusion coefficients, K, are functions of both position in the estuary and flow of the Merrimack River. The average weekly flow rate of the Merrimack is given in Figure 2. If sufficient data were available, EQ. [6] could be integrated over x and solved for σK. There were not sufficient observations for the Merrimack River to perform this integration. Since Boicourt's model for the Upper Chesapeake

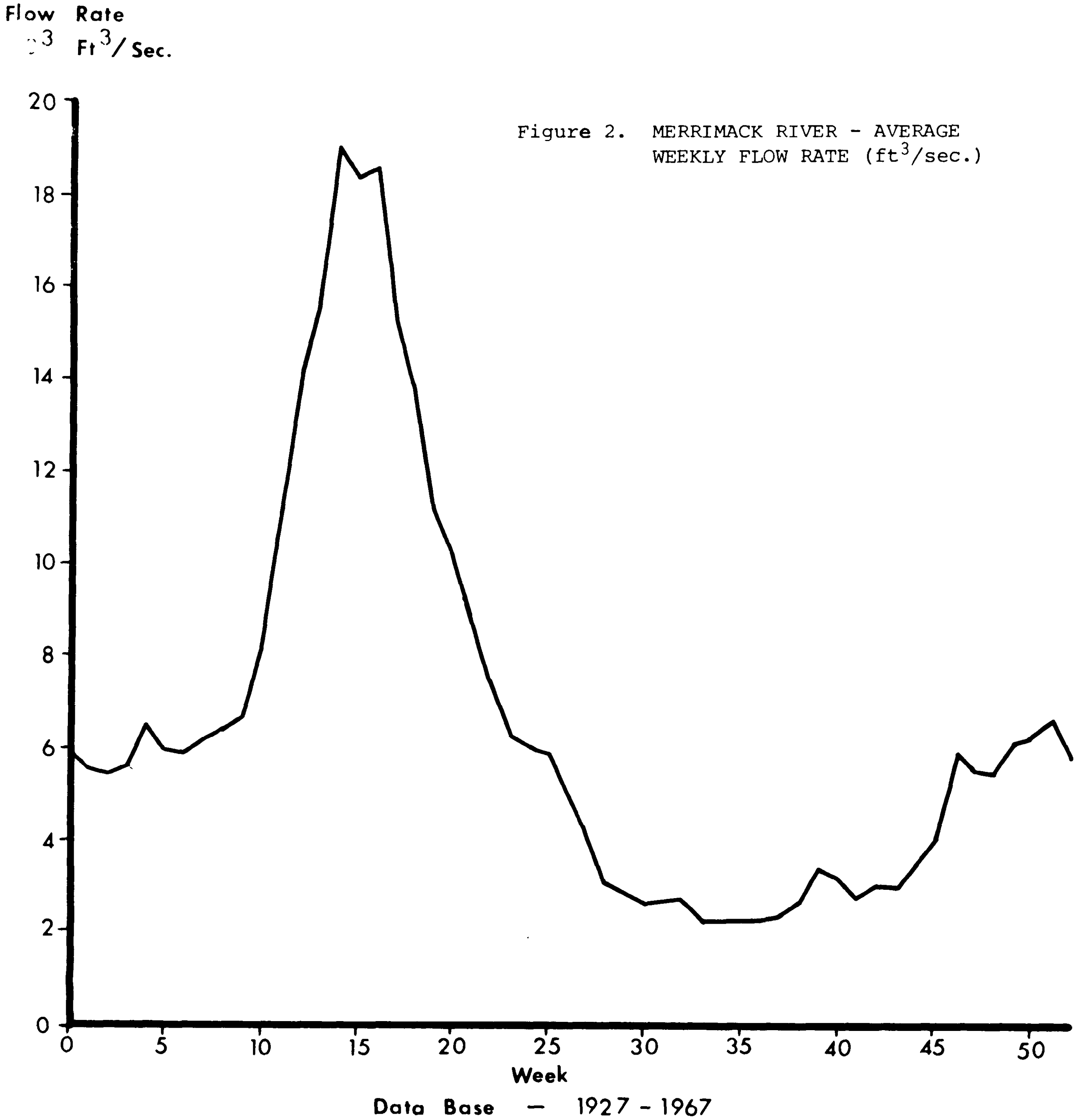


Figure 2. MERRIMACK RIVER - AVERAGE WEEKLY FLOW RATE (ft^3/sec.)

Bay was used as the basis for the model for the Merrimack River it was decided to see if K values could be transferred. The cross-sectional areas, σ, were known for both estuaries, hence, K values could be recovered from the Cheskapeake σK values (Figure 3).

Boicourt (1969) used the form

$$\sigma K = \exp\,[C_o + C_1\, x]. \qquad [9]$$

The coefficients C_o and C_1 were determined by a least-squares fit to 1966-67 data. Two functions were developed to relate the coefficients to river flow:

$$C_o = A_o\,(\log R)^{B_o} \qquad [10]$$

where $A_o = 7.724$ $\qquad B_o = .3580,$

and $C_1 = A_1\,(\log R)^{B_1}$ $\qquad [11]$

where $A_1 = .6138$ and $B_1 = 1.498$

and R is the average weekly river flow (m^3/second).

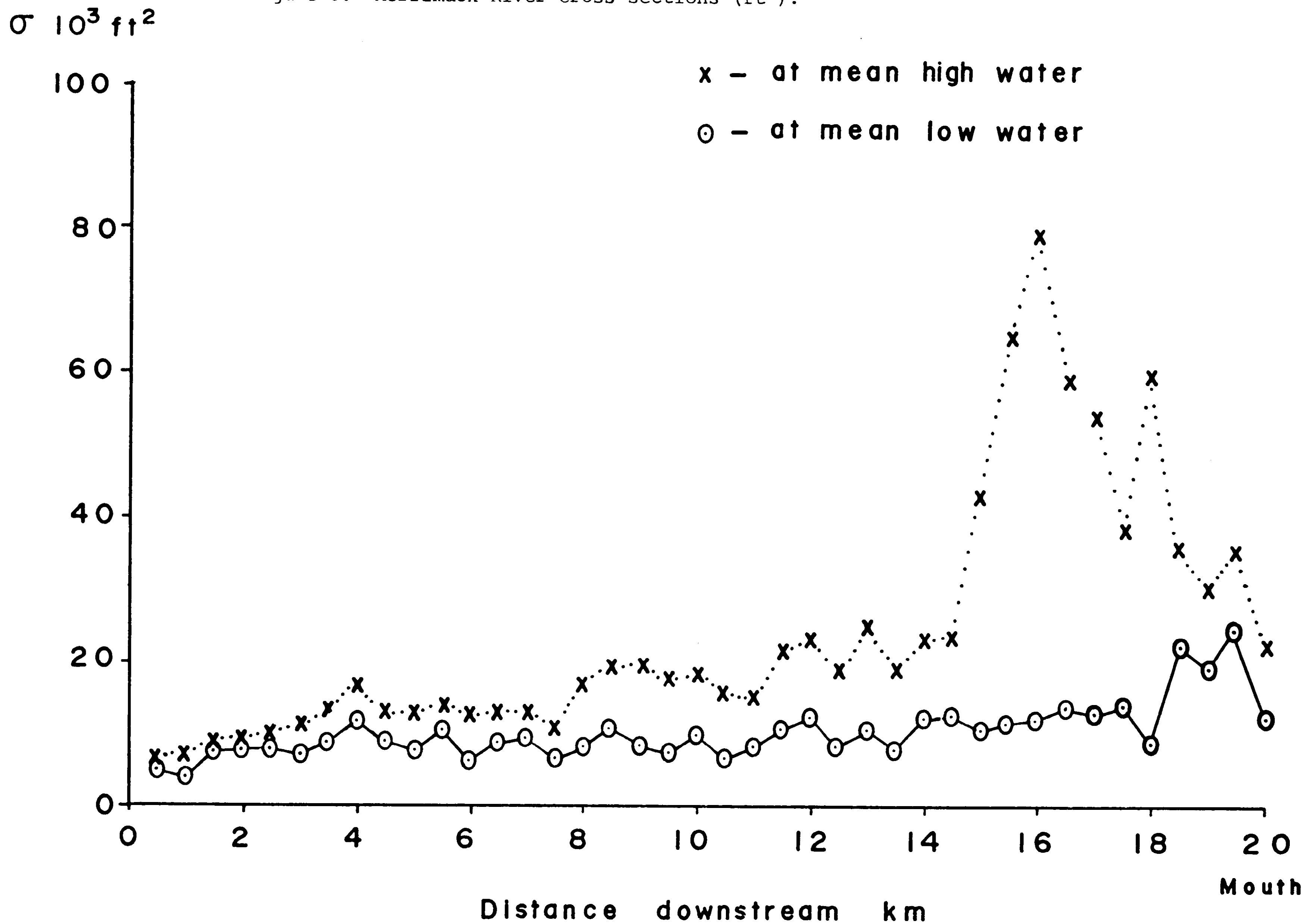
EQ. [9] may be rewritten

$$\ln \sigma K = C_o + C_1\; x \qquad [9a]$$

and given σ as function of x, a new equation for K can be determined,

$$\ln K = H_o + H_1\, x \qquad [12]$$

Figure 3. Merrimack River Cross-sections (ft^2).



III-17.

$$H_o = \exp [0.460 + 0.1955 \ln R] \quad [13]$$

$$H_1 = \exp [-3.17 - .00287 R] \quad [14]$$

These values provide a good average salinity over both estuaries but for salinity at high or low tide the coefficients must be modified. Using the limited data available for the Merrimack River, the coefficients in Table I were determined to provide an acceptable fit to observations.

The upstream boundary value was set to 0 while the boundary value at the mouth of the river was found to be a function of river flow and tide stage. The boundary values used in the mathematical model are shown in Figure 4.

In summary, the major assumptions made in this development include the following:

1) Salinity values used in the model are averages over the cross-section of the estuary and that variables are related only to time and position along the longitudinal axis of the estuary.

2) Molecular diffusion is negligible.

3. That eddy diffusion can be treated in a manner analogous to molecular diffusion that is as a product of a diffusivity and a

SALINITY STUDY, MERRIMACK RIVER ESTUARY

MATHEMATICAL STUDY

TABLE L

COEFFICIENTS FOR K - MERRIMACK RIVER

High Tide

$$H_o = \exp\ [0.23 + 0.10 \ln R]$$

$$H_1 = \exp\ [-1.6 - .015\ R]$$

Low Tide

$$H_o = \exp\ [0.46 + 0.19 \ln R]$$

$$H_1 = \exp\ [-3.0 - .003\ R]$$

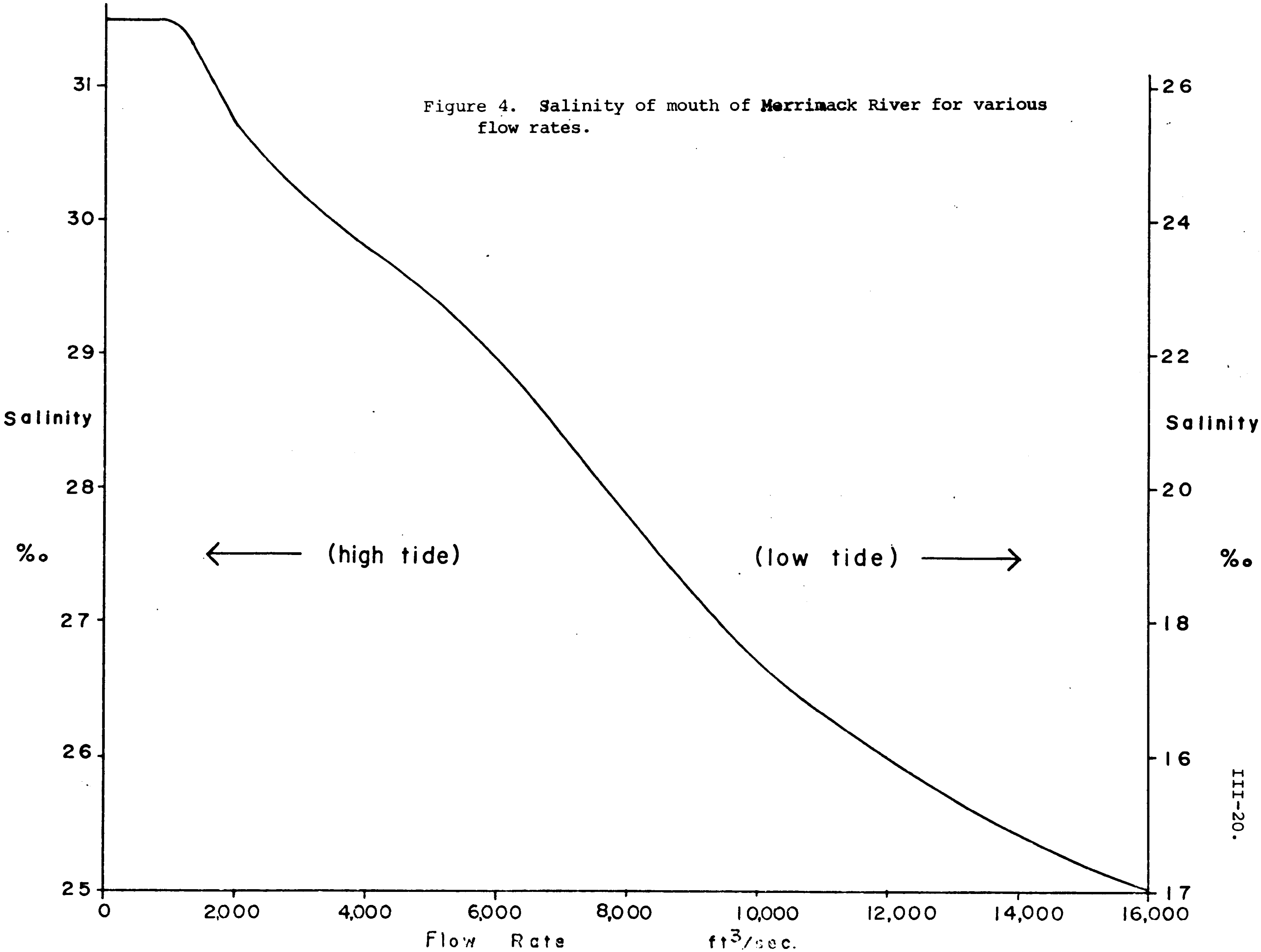


Figure 4. Salinity of mouth of Merrimack River for various flow rates.

gradient. (Note that in this study diffusivity is taken as a function of space and time.)

4) The tidal currents are assumed to advect a fixed salinity pattern periodically up and down the estuary. (This assumption allows measurements made and one phase of the tide to be treated as averages over the tidal cycle.)

5) That the Merrimack River's salinity distribution has little time history effect.

6) That the Merrimack River can be treated as nearly sectionally homogeneous.

7) Effects of the earth's rotation are assumed to be negligible.

4. Solution

The finite difference equation [8] with the addition of the two boundary conditions, forms a set of N simultaneous linear equations in N unknowns, where $N\Delta x$ is the length of the estuary. Given an initial salinity distribution $S(x)$, the salinity at a time Δt later can be determined by inverting the matrix of the $S'(x)$ coefficients. A convenient method for this inversion is to triangularize and then solve for the $S'(x)$ via back substitution (Gauss elimination; see Hildebrand, 1968). The tridiagonal nature of the matrix fortuitously reduces the triangularization procedure to a recursive sweep over x space. This sweep consists of computing the space functions Q(x) and P(x) (Pritchard, 1969):

$$Q(x) = \frac{-P_R(x)}{1 + P_L(x)Q(x-1)}$$

$$P(x) = \frac{\frac{S(x)}{P_C(x)} - P_L(x)P(x+\Delta x)}{1 + P_L(x)Q(x-\Delta x)}$$

where P_L, P_R, and P_C are coefficients in equation [8].

Back substitution, which produces the S'(x) values, consists of a recursive sweep in the opposite direction:

$$S'(x) = P(x) + Q(x)S'(x+\Delta x)$$

The resulting S'(x) became the S(x) for the next time step, where a new set of difference equations are formed from the new coefficients computed from the new value of the river flow.

5. Testing and Evaluation

The predicting functions for the coefficients and boundary values were tested against salinity data obtained during the years 1967 to 1971. The model is supposed to predict weekly average salinity values. Some of the observed data represent only two days. The plotted results are shown in Figure 5. The results appear to be quite

Figure 5a. Comparison of Observed and Calculated Salinity Distributions in the Merrimack River.

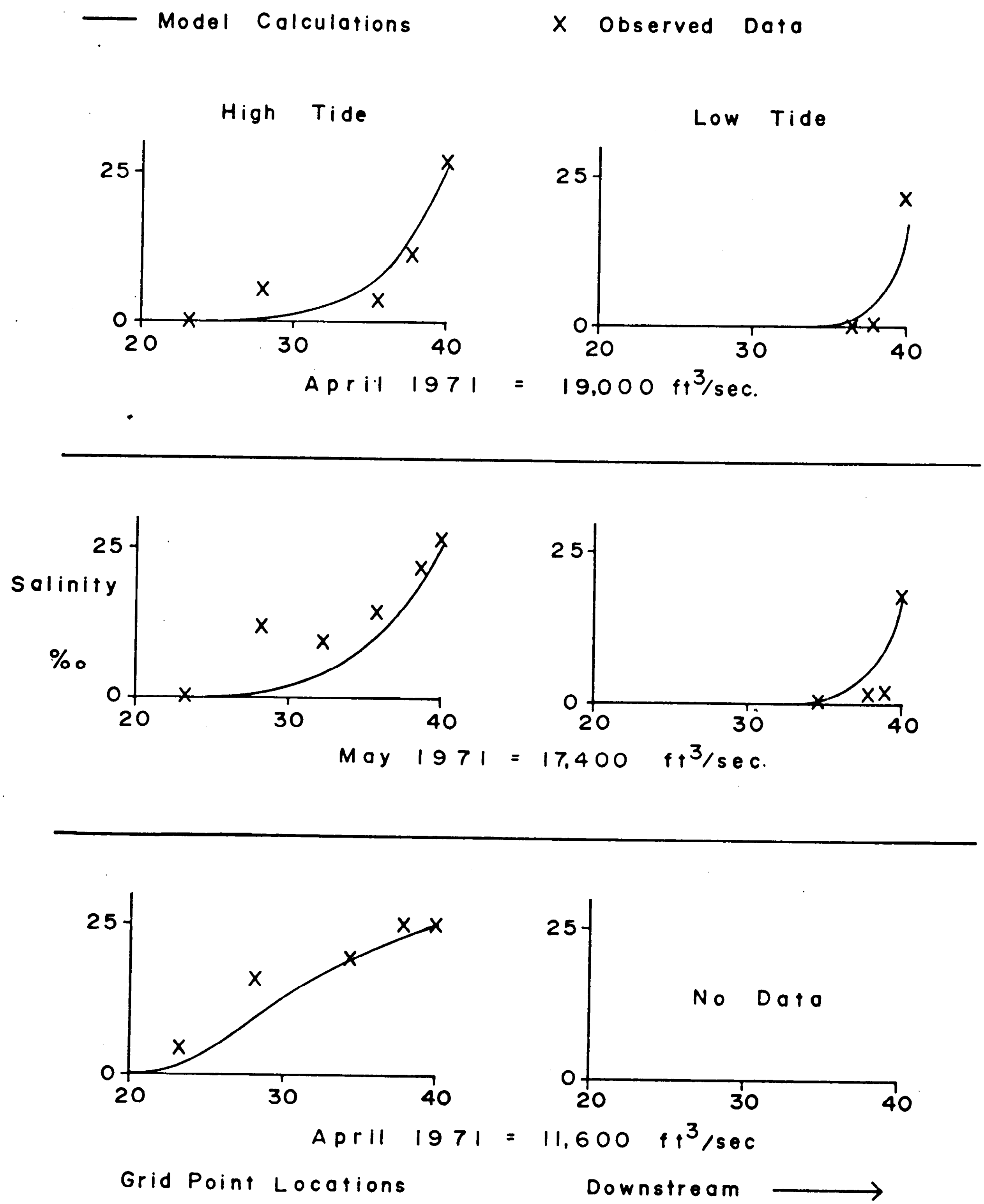


Figure 5b. Comparison of Observed and Calculated Salinity Distributions in the Merrimack River.

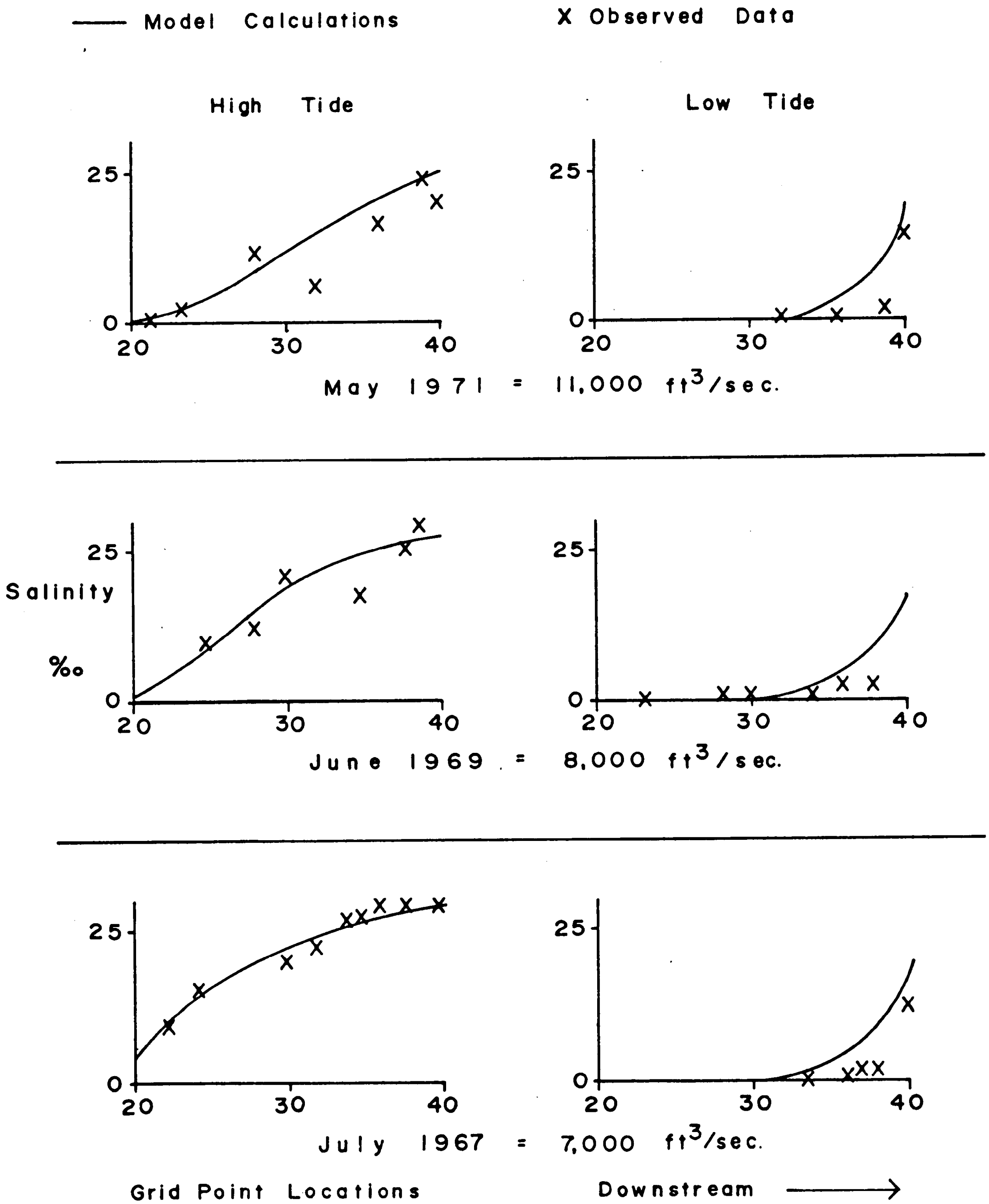
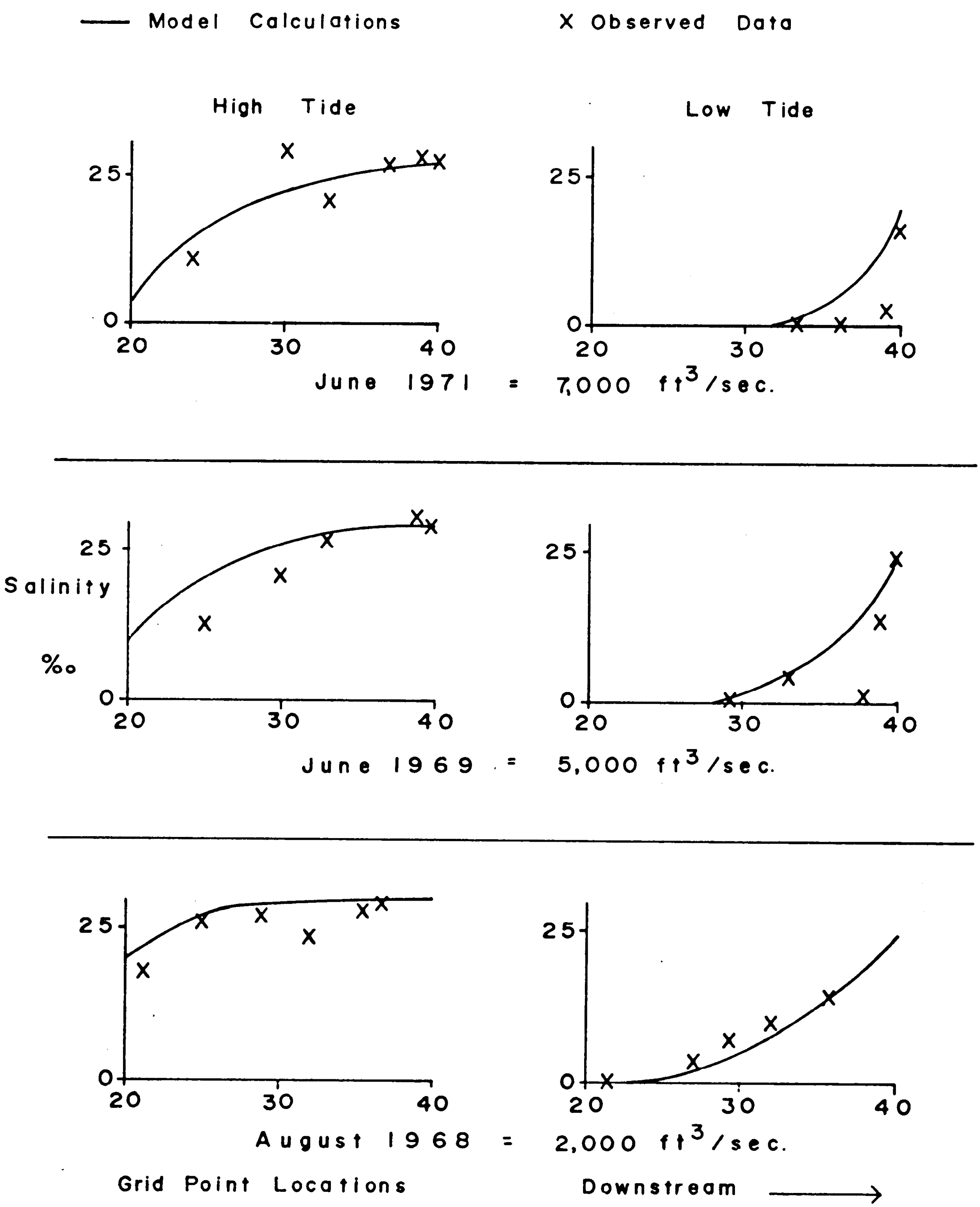


Figure 5c. Comparison of Observed and Calculated Salinity Distribution in the Merrimack River.



reasonable. There is a tendency for the model to overpredict in the two kilometers immediately upstream of the mouth of the river at high flow rates, (i.e., greater than 5,000 cfs, for low tide).

More verification is needed at flow rates less than 5,000 cfs. There was only one observation at 2,000 cfs and the model appeared to overpredict slightly for high tide. Since the coefficients determining the diffusion rates are based on the observed data, the use of the model outside the range of validation should be done with caution.

6. Principal Limitations

The principal limitation of the mathematical model of the Merrimack River Estuary is that the vertical and horizontal gradients are not considered. Since there is not sufficient seasonal and spatial data to justify a more elaborate model, a one-dimensional model in space has been used. Of principal importance to the ecological study is the limit of salt intrusion and the average salinity at the various stations. The verification studies reported in the paragraph above indicate that these methods have been justified with respect to the vertically averaged salinity values and the limit of salt intrusion in the estuary. Thus a one-dimensional model can satisfactorily represent the average distribution of salinity in the Merrimack River, but it is inadequate for those who require information on the vertical distribution. However, in the region of the salt front where the horizontal salinity gradients are the greatest and the vertical salinity gradients the weakest, the model can be used directly as a first approximation to the salinity structure. For more vertically stratified conditions such as those which occur in the lower reaches of the estuary during moderately low flows at high tide it is possible to refer to other information such as a "typical" salinity-depth curve to obtain an indication of the possible salinity values in the upper and lower layers.

D. RESULTS

The results of the mathematical model are presented as a series of computer printouts in graphic form. The method of indexing the graphic charts has been arranged for the greatest possible user convenience consistent with the detail of the information required. Sensitivity studies were made to determine the effect of small changes in runoff on the salinity distribution. These studies indicated that incremental changes of less than 100 cfs at the low ranges and 2,000 cfs at the high ranges have little effect on the model and further that the recent time history of flow also has very little effect on the model. Hence, it has been possible to devise a diversion index, Table II., which summarizes and keys them to the graphic charts.

1. The Diversion Index

Natural flows are tabulated in the left hand "flow" column of

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TABLE II.

DIVERSION INDEX

FLOW \ DIVERSION (Cubic Feet per Second)	100	200	300	500	600	800	1000	1100	1500	1900	2000	2800	5200	8000
800														
850														
900														
950	2													
1000	3							1*						
1100	5	3												
1200	6	5	3											
1300	7	6	5											
1400	8	7	6	3										
1500	9	8	7	5	3									
1600	10	9	8	6	5									
1700	11	10	9	7	6	3								
1800	12	11	10	8	7	5								
1900	13	12	11	9	8	6	3							
2000	14	13	12	10	9	7	5	3						
3000	16	16	16	15	15	15	15	15	10	5	5			
4000	17	17	17	17	16	16	16	16	15	15	15	7		
5000	18	18	18	17	17	17	17	17	17	16	16	15		
6000	19	19	19	19	18	18	18	18	17	17	17	16		
7000	20	20	20	19	19	19	19	19	19	18	18	17	13	
8000	21	21	21	21	20	20	20	20	19	19	19	18	16	
10000	22	22	22	22	22	22	21	21	21	21	21	20	18	15
12000	23	23	23	23	23	23	22	22	22	22	22	22	20	17
14000	24	24	24	24	24	24	24	23	23	23	23	23	21	19
16000	25	25	25	25	25	25	25	24	24	24	24	24	22	21
cfs														

*All blank table entries refer to Figure 1 of Appendices A and B for high and low tides, respectively. Figures 1 (A & B) represent the minimum control flow established by the Corps of Engineers.

Although natural flows in river frequently occur below 800 cfs, salinity profile plots were not carried out below 800 cfs because this represents the minimum flow beyond which diversions are not contemplated.

the diversion index. The various diversion rates are listed across the top of the table. The index numbers represent the appropriate figure of Appendix "A" for the high tide case and also the appropriate figure of Appendix "B" for the low tide case. For example, when the river flow is 1,800 cfs, the diversion index number is 10. Thus, the appropriate figure in the salinity atlas is A-10 for the high tide case and B-10 for the low tide case. Appendix "C" is a listing of the weekly average flow rates from 1927 to 1967. Weekly flow rates instead of monthly flow rates have been used since the estuary responds to different flow rates quickly enough to warrant additional detail. To use the index, select the flow and diversion to be investigated; at the intersection of the columns (diversions) and horizontal lines (flows) will be found the index number. The index number references the applicable figure number of the graphical computer printouts of longitudinal salinity for the Merrimack River Estuary.

2. Graphic Computer Printout

The graphic computer printout is a plot of the computed vertical average of salinity at high tide (low tide) weighted by the width of the estuary. The units of the horizontal coordinate are one-half kilometer intervals. Table III keys the Normandeau Associates station numbers to the graphic printout one-half kilometer intervals. The vertical coordinate represents the vertical weighted average salinity in the range of 0 to 35 parts per thousand (S^{o}/oo). Figure 6 is the salinity station and half-kilometer grid point key.

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TABLE III

SALINITY STATION AND HALF-KILOMETER GRID POINT

KEY

NORMANDEAU ASSOCIATES, INC. STATION NUMBER	ONE-HALF KILOMETER INTERVAL SHOWN OF GRAPHIC PRINTOUTS
S 1	40 (mouth of estuary)
S 2	39
S 3	37
S 3A	31
S 4	29
S 5	24
S 6	11
S 7	- 3 (head of estuary)

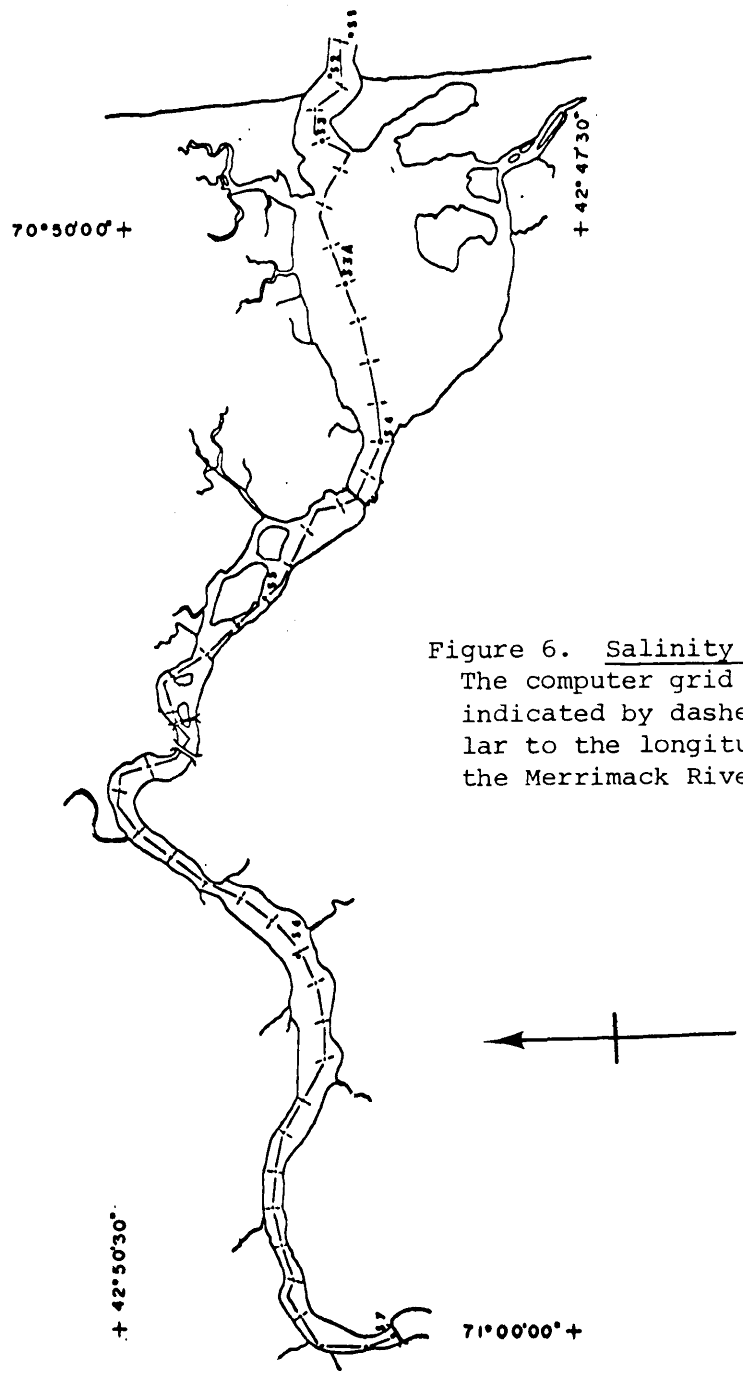


Figure 6. Salinity Station Key
The computer grid points are indicated by dashes perpendicular to the longitudinal axis of the Merrimack River Estuary.

Approximate Scale: 1:93,600

3. Summary

The salinity distribution in the Merrimack River Estuary has been modeled using a model based on the one-dimensional salt balance equation of Pritchard. The results of the computations have been presented in graphical form, keyed to the runoff values and proposed diversions by an index.

The results of the computations indicate a seaward progression of the salt from grid point 5 at 800 cfs to grid point 26 at 16,000 cfs for the high tide case. For the low tide case the corresponding progression is from grid point 18 at 800 cfs to grid point 35 at 16,000 cfs. For higher flows the salt front is essentially removed from the estuary and detailed computations are not necessary. These results are in agreement with physical reality in the important characteristics and trends. Thus, it is concluded the model is a useful one which could be utilized for other purposes in future planning for the Merrimack Basin.

The one-dimensional model used in this study is of value for two reasons: 1) it furnishes the desired predicting ability and it also provides a base from which more elaborate models can be developed; 2) of immediate practical interest would be the addition of the ability to model BOD loading using this model as a basis. The regional planning regarding the effects of sewer or other outfalls could be implemented using this model as a basis.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

IV. POTENTIAL EFFECTS OF DIVERSION ON THE

PHYSICAL CHARACTERISTICS OF THE ESTUARY

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

IV. POTENTIAL EFFECTS OF DIVERSION ON THE PHYSICAL CHARACTERISTICS OF THE ESTUARY

A. INTRODUCTION

A rapidly expanding body of knowledge on the effects of river diversions on the physical characteristics of rivers and estuaries is becoming available. Much of this information was covered in general terms at the New England Conference on River Diversions, held at the New England Center for Continuing Education, Durham, New Hampshire, in May 1971 (Forste, R. H., Editor, 1971). As was pointed out at that time, even though many of the consequences associated with particular river diversions are unique to those rivers, other effects are comparable to those encountered in all potential diversion cases.

These effects fall into two categories. With any diversion, certain substances are removed directly from the system, including freshwater, dissolved and particulate organic material, freshwater plankton, trace elements, and sediments. The removal of these substances may lead to direct physical changes in the system, including some or all of the following:

1. Salinity increase.
2. Changes in sedimentation.
3. Alteration of current flow.
4. Reduction of temperature extremes.
5. Changes in the effect of pollution load.
6. Difference in dissolved O_2.
7. Changes in transparency.

Some of these changes have potentially serious effects on the ecology of the estuary, while others appear to be of minimal importance. In some instances further study must be done before definite conclusions can be drawn. Those physical changes that appear to be of potential ecological significance to the estuary will be discussed in the following pages.

B. LONGITUDINAL CHANGES IN SALINITY DISTRIBUTION

Results of VAST's mathematical model, as well as other salinity measurements made during 1971 and earlier findings reported by Hartwell (1970), indicate that under high discharge the Merrimack River Estuary is essentially fresh throughout most of the tidal cycle. Saline water progresses further upstream as discharge drops. Based on this information and a knowledge of suggested diversion rates and minimum flows below which diversions will not be made, it is possible to evaluate the consequences of potential changes in longitudinal salinity patterns resulting from diversion.

Natural flows in the Merrimack River rarely drop below 800 cfs on an average weekly basis (Appendix C). This occurred only twice in a 40 year period and, in fact, average flows were below 1,000 cfs during less than 1% of the 2,080 weeks studied. The latter flows were experienced during 18 weeks distributed over four of the 40 years involved, namely 1957, 1964, 1965, and 1966. Average flows less than 1,500 cfs occurred during 24 of the 40 years, the total number of weeks involved being 138, or 7% of the 2,080 week period.

The daily operational pattern of the several dams along the Merrimack River is such that river flows fluctuate markedly within a week. While the number of high flow days is greater than the number of low flow days, hence the two to three thousand cfs rate shown during summer months (Figure 7a), flow rates well below 800 cfs do occur periodically. This is reflected in monthly averages of the daily minima which occurred from 1924 to 1969 during July, August, and September, which are 1,026, 772, and 778 cfs, respectively. These naturally occurring average minima are below the control levels established for the river for the July-September period (Section I).

We conclude from these facts that upriver areas presently affected by salt water intrusion only periodically, such as between miles 5 to 10, may be subjected to more frequent saline influence due to diversion. This should not represent an entirely new experience however. The effects of diverting water at several different rates

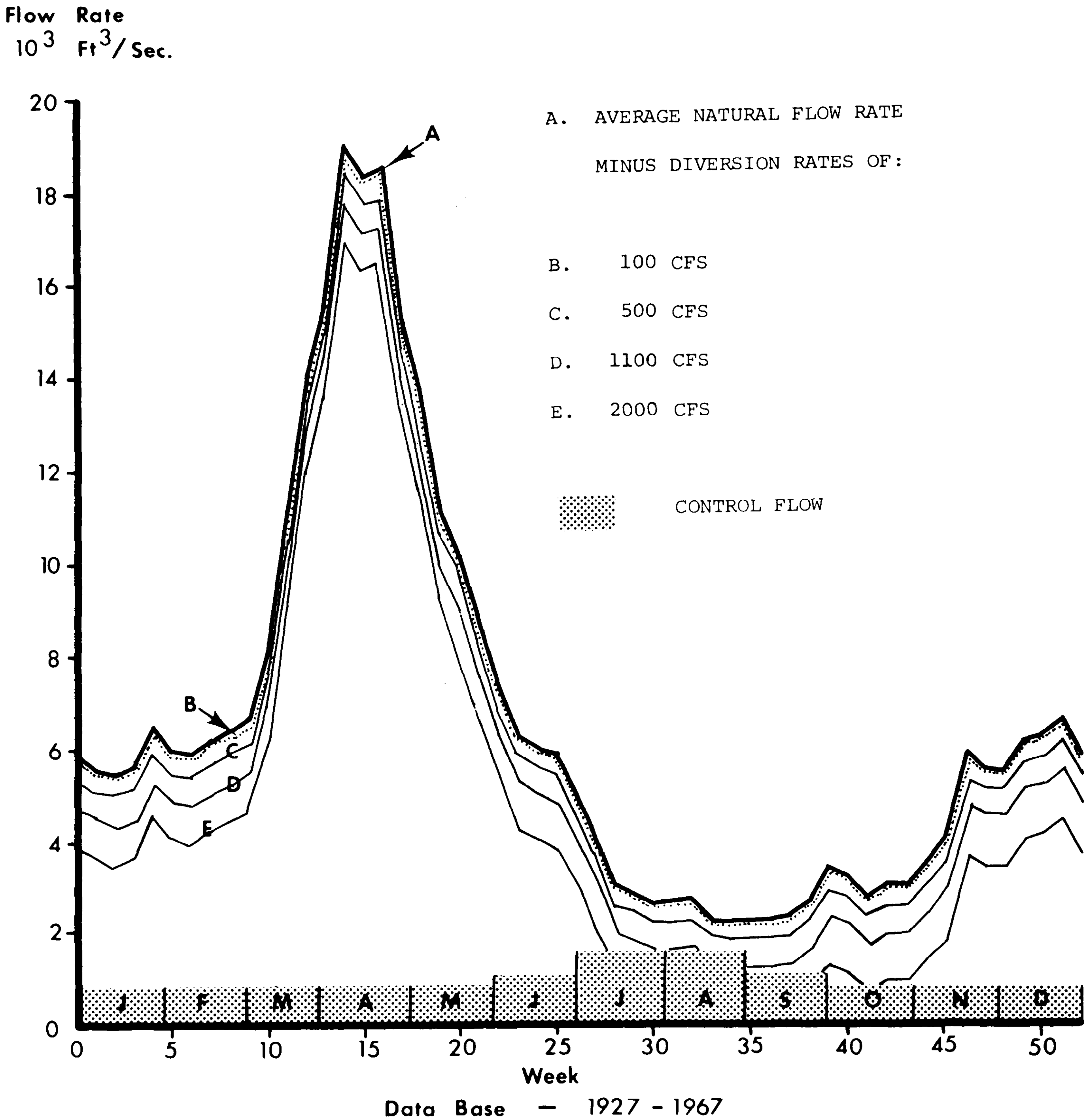


Figure 7a. COMPARATIVE EFFECTS OF SEVERAL DIVERSION RATES ON THE SEASONAL FLOW PATTERN IN THE MERRIMACK RIVER.

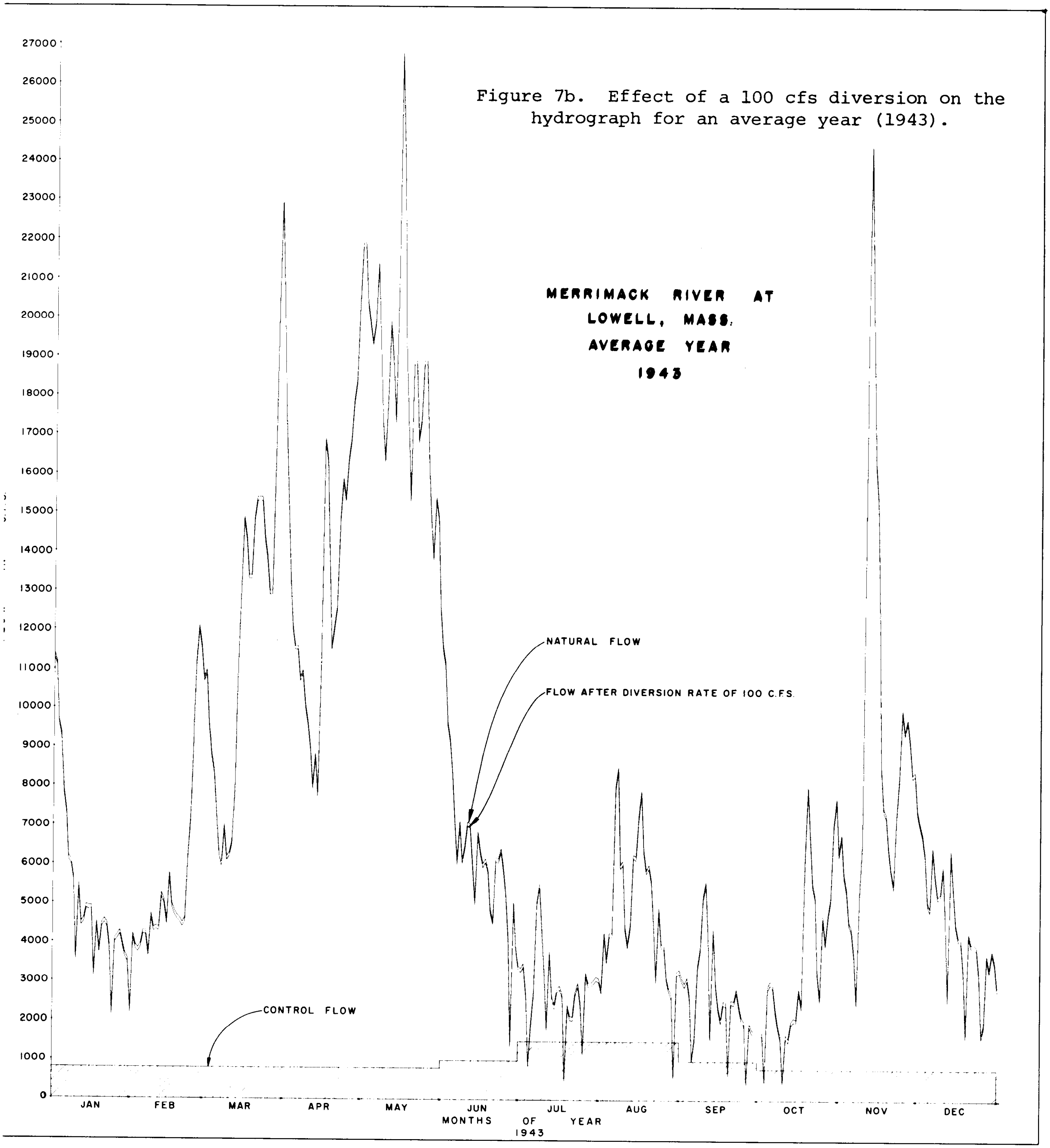


Figure 7b. Effect of a 100 cfs diversion on the hydrograph for an average year (1943).

Figure 7c. Effect of a 500 cfs diversion on the hydrograph for an average year (1943).

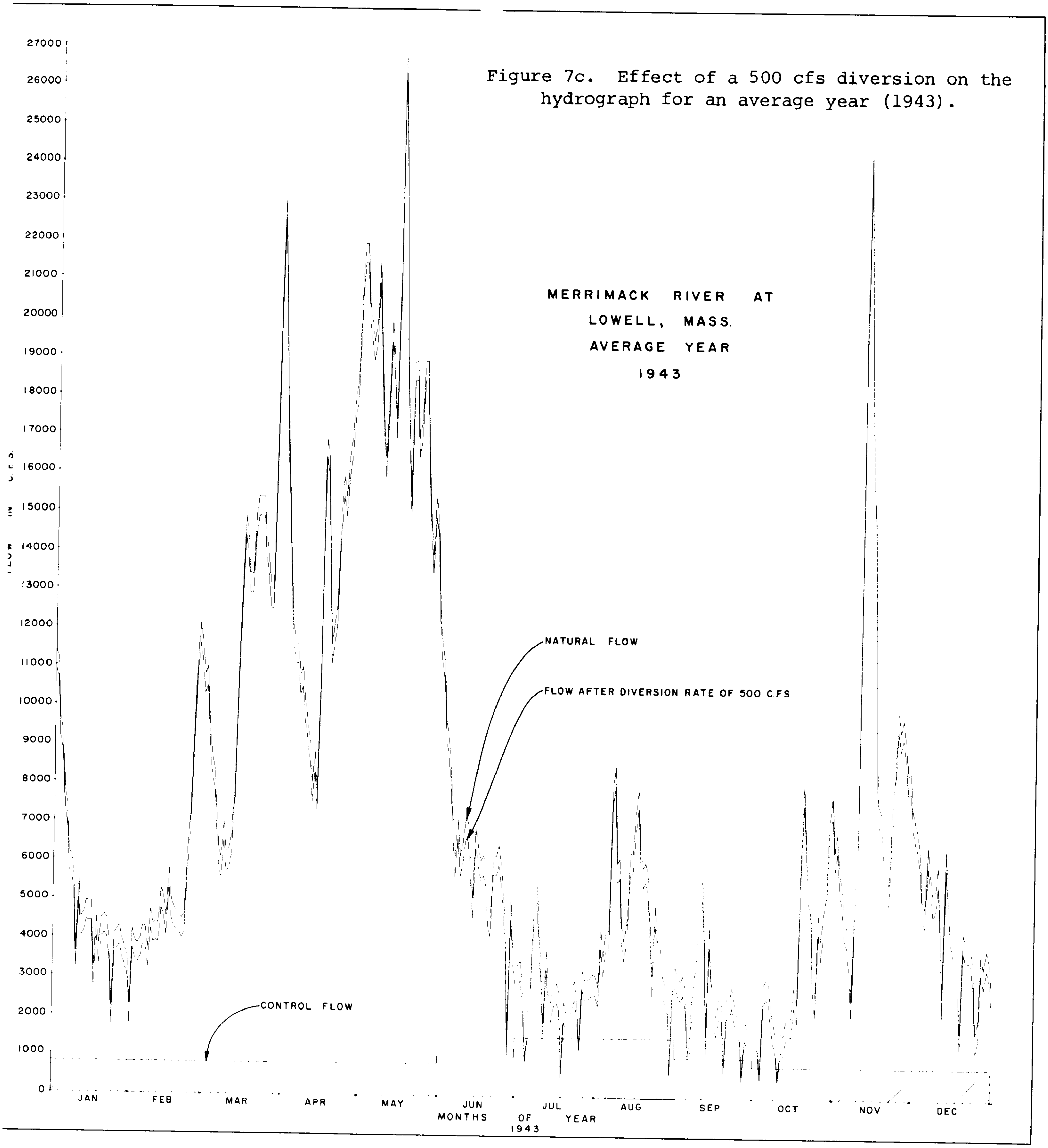
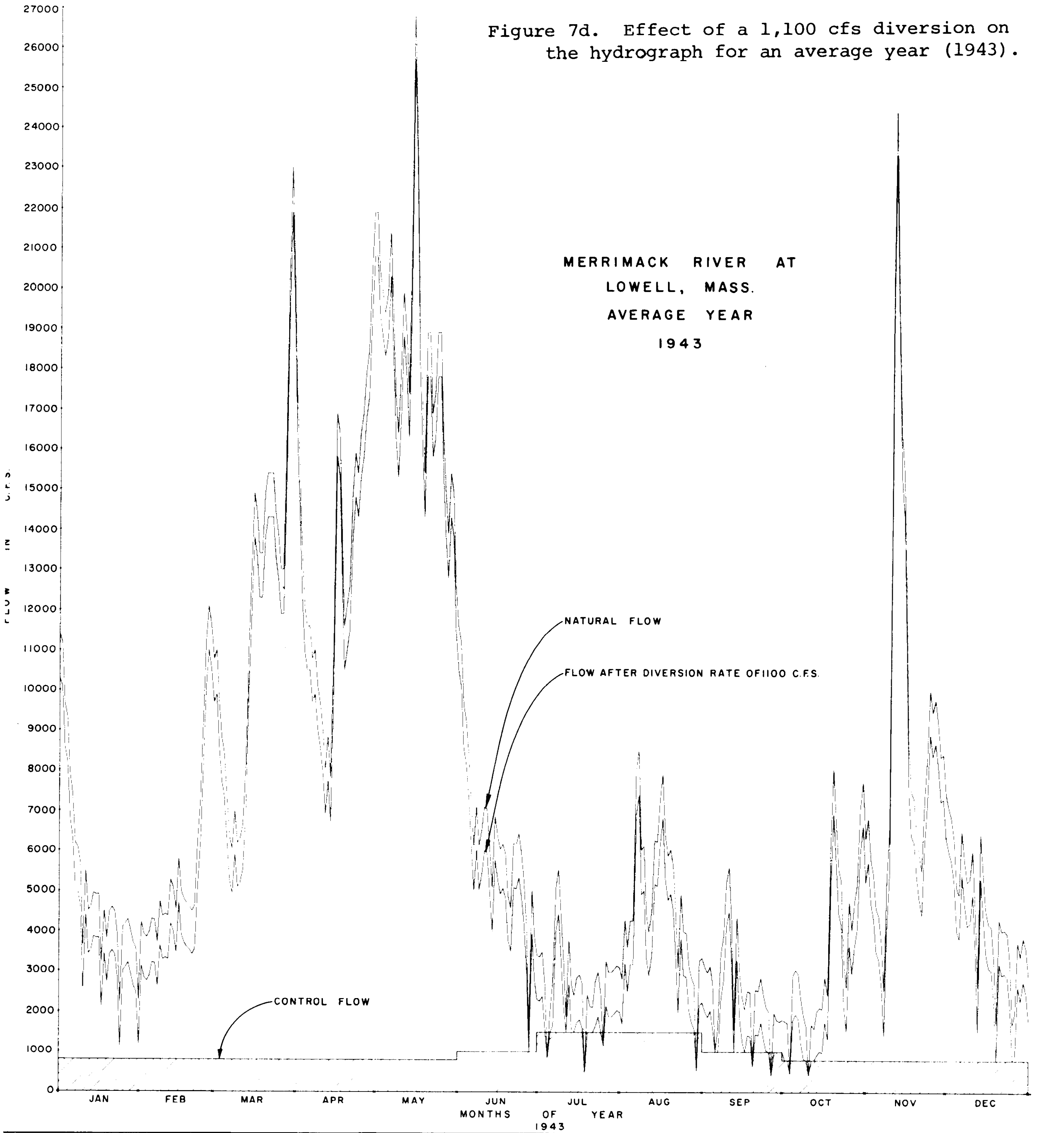


Figure 7d. Effect of a 1,100 cfs diversion on the hydrograph for an average year (1943).



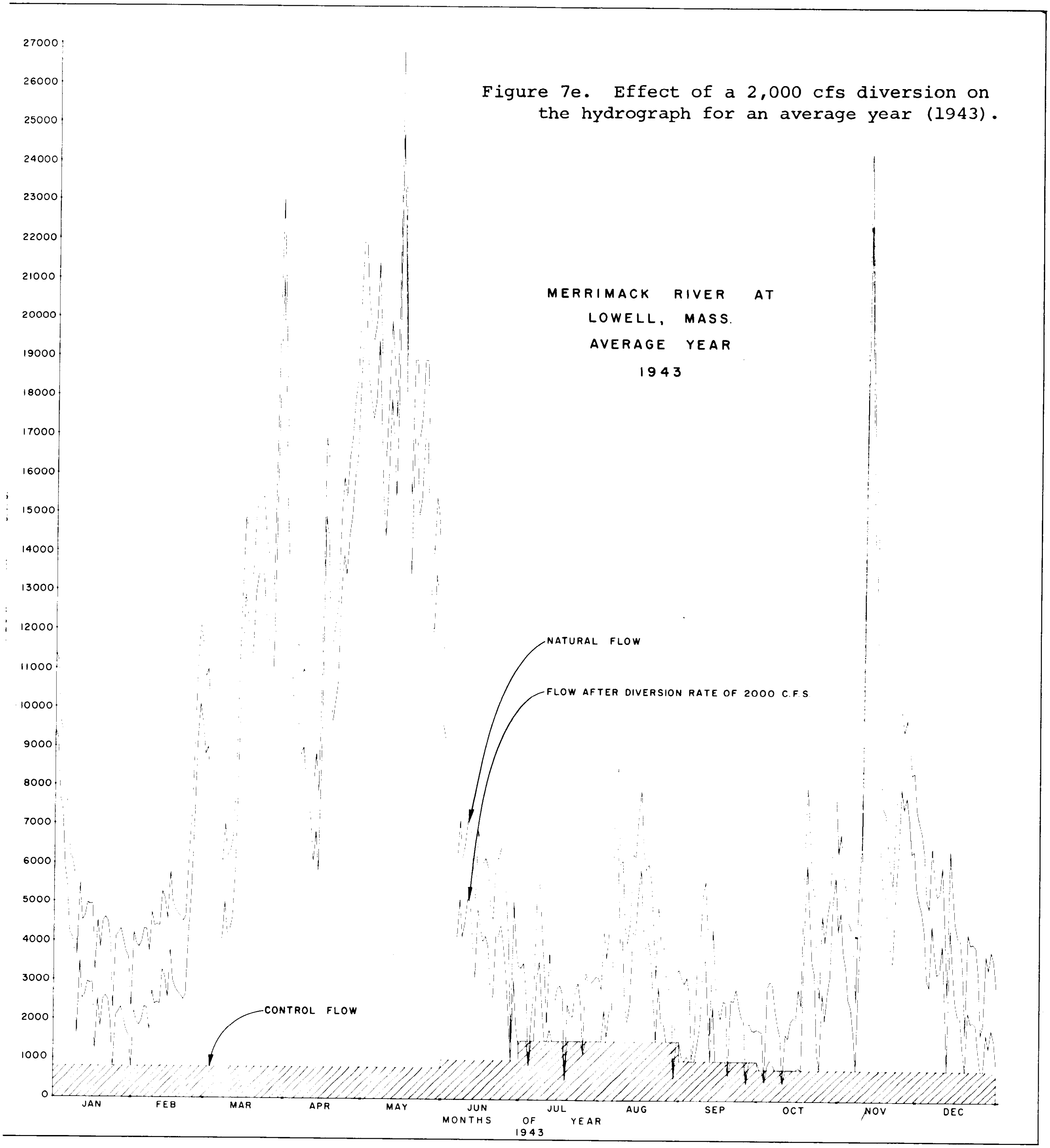


Figure 7e. Effect of a 2,000 cfs diversion on the hydrograph for an average year (1943).
MERRIMACK RIVER AT
LOWELL, MASS.
AVERAGE YEAR
1943
NATURAL FLOW
FLOW AFTER DIVERSION RATE OF 2000 C.F.S
CONTROL FLOW
27000
26000
25000
24000
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS OF YEAR
1943

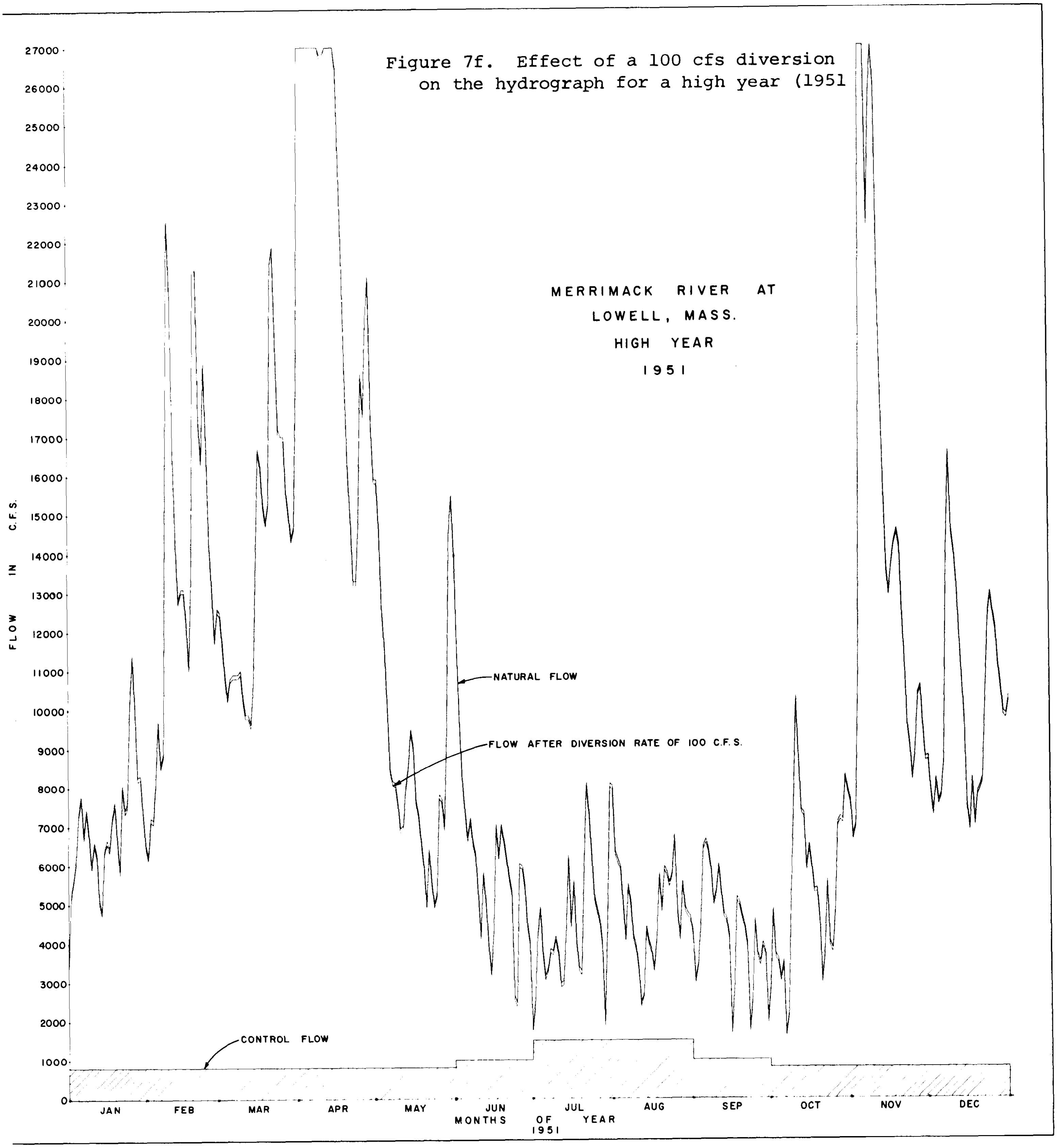
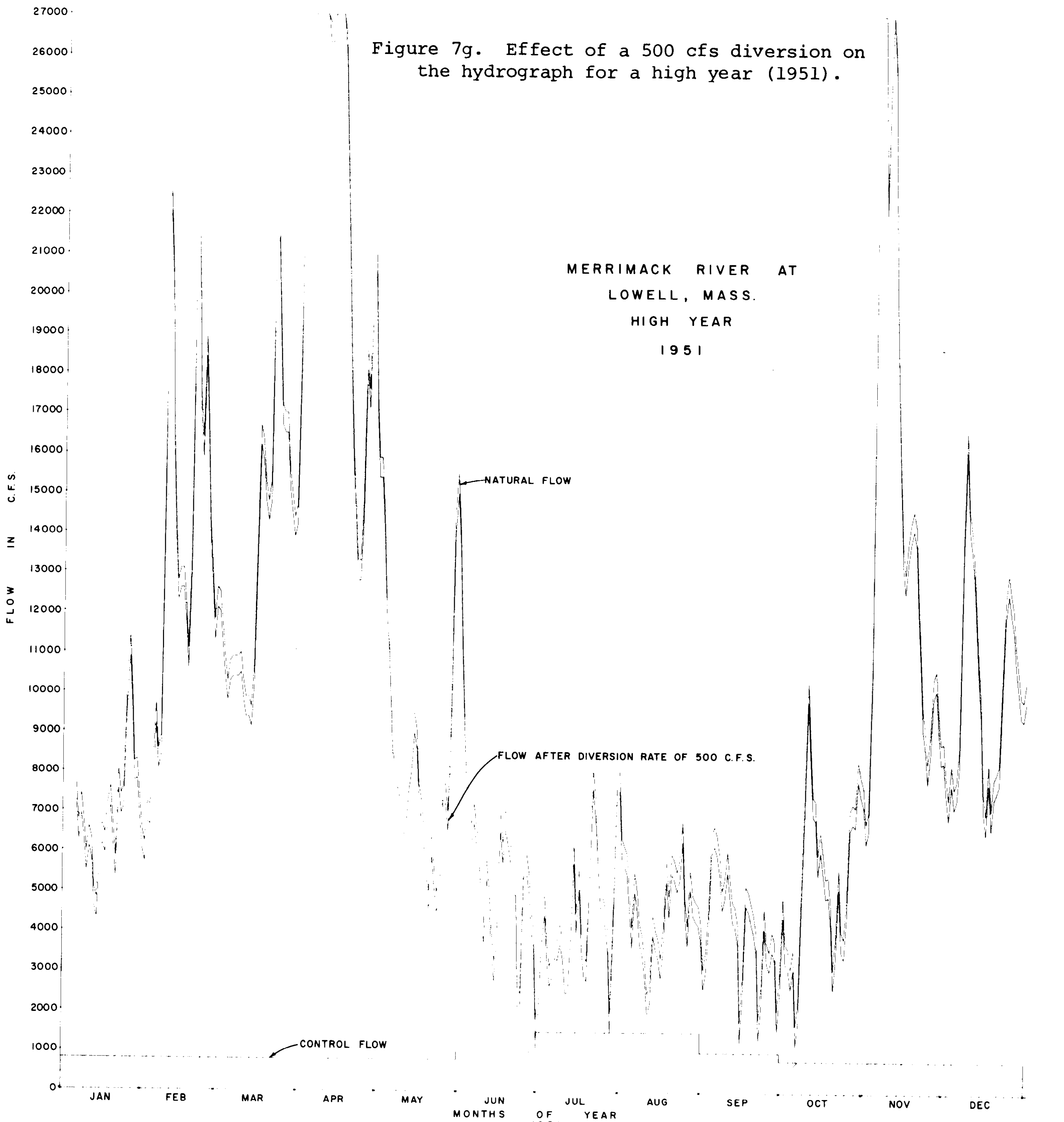


Figure 7f. Effect of a 100 cfs diversion
on the hydrograph for a high year (1951
MERRIMACK RIVER AT
LOWELL, MASS.
HIGH YEAR
1951
NATURAL FLOW
FLOW AFTER DIVERSION RATE OF 100 C.F.S.
CONTROL FLOW
FLOW IN C.F.S.
27000
26000
25000
24000
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS OF YEAR
1951

Figure 7g. Effect of a 500 cfs diversion on the hydrograph for a high year (1951).



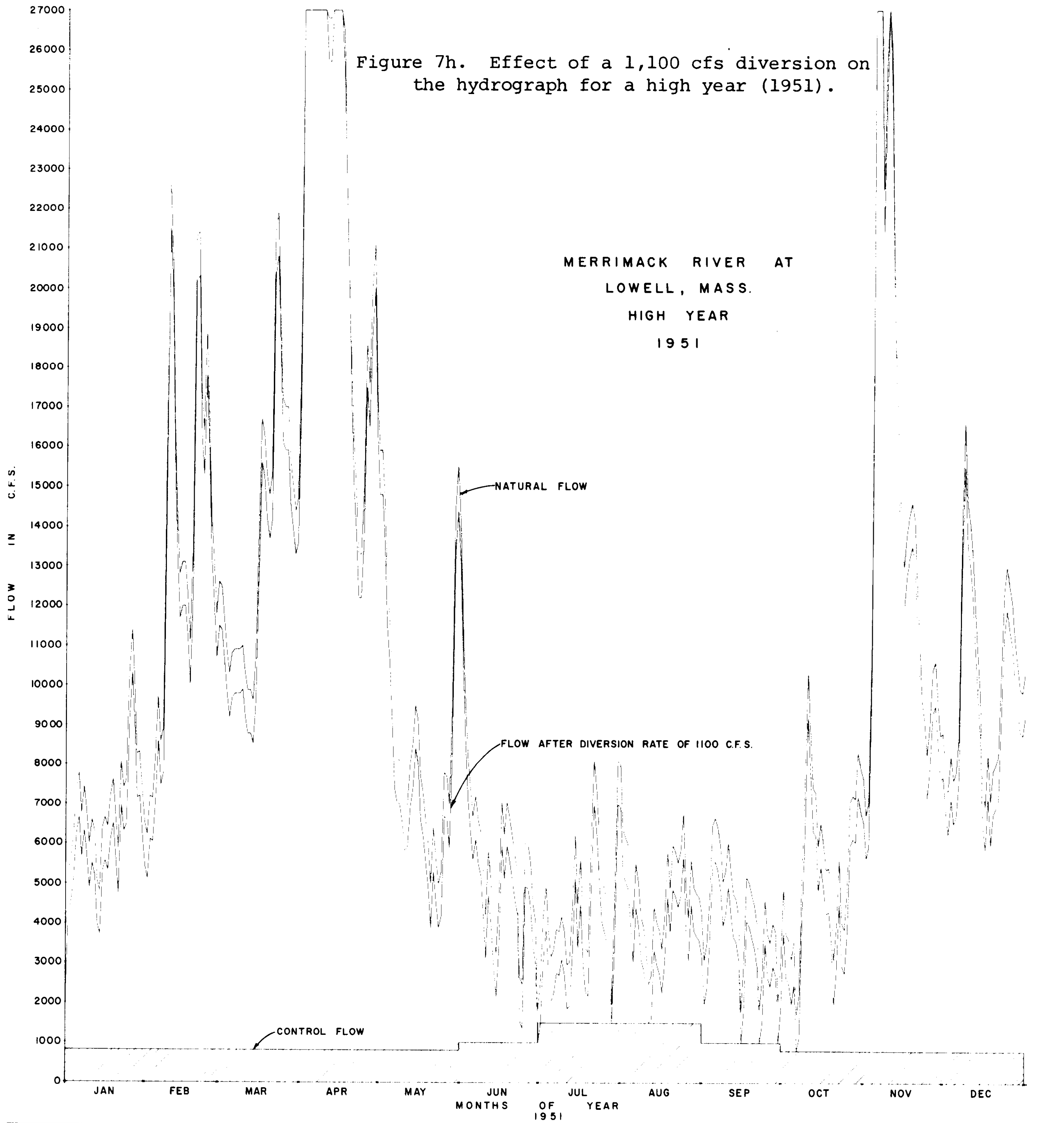


Figure 7h. Effect of a 1,100 cfs diversion on the hydrograph for a high year (1951).

Figure 7i. Effect of a 2,000 cfs diversion on the hydrograph for a high year (1951).

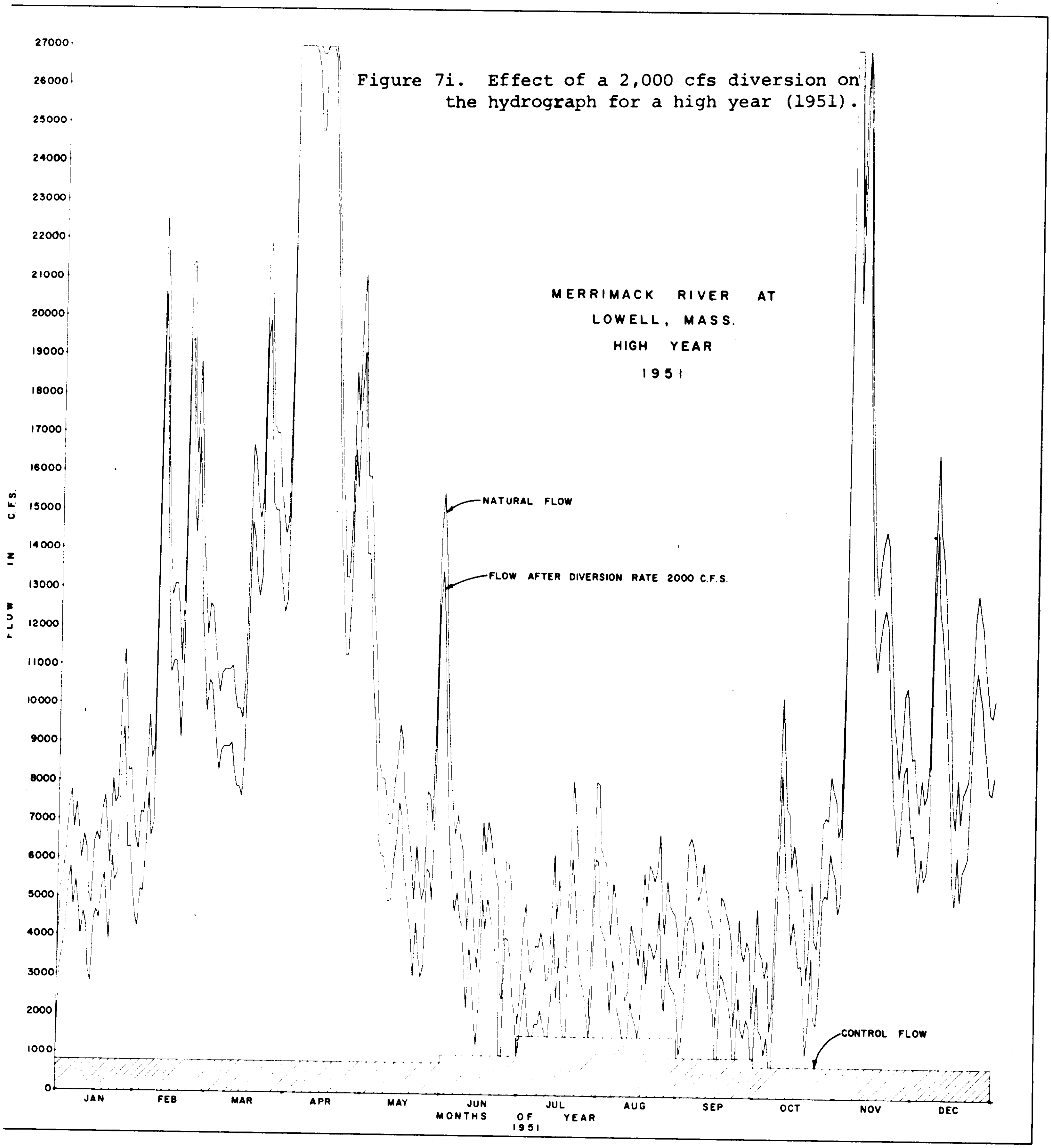


Figure 7j. Effect of a 100 cfs diversion on the hydrograph for a dry year (1965).

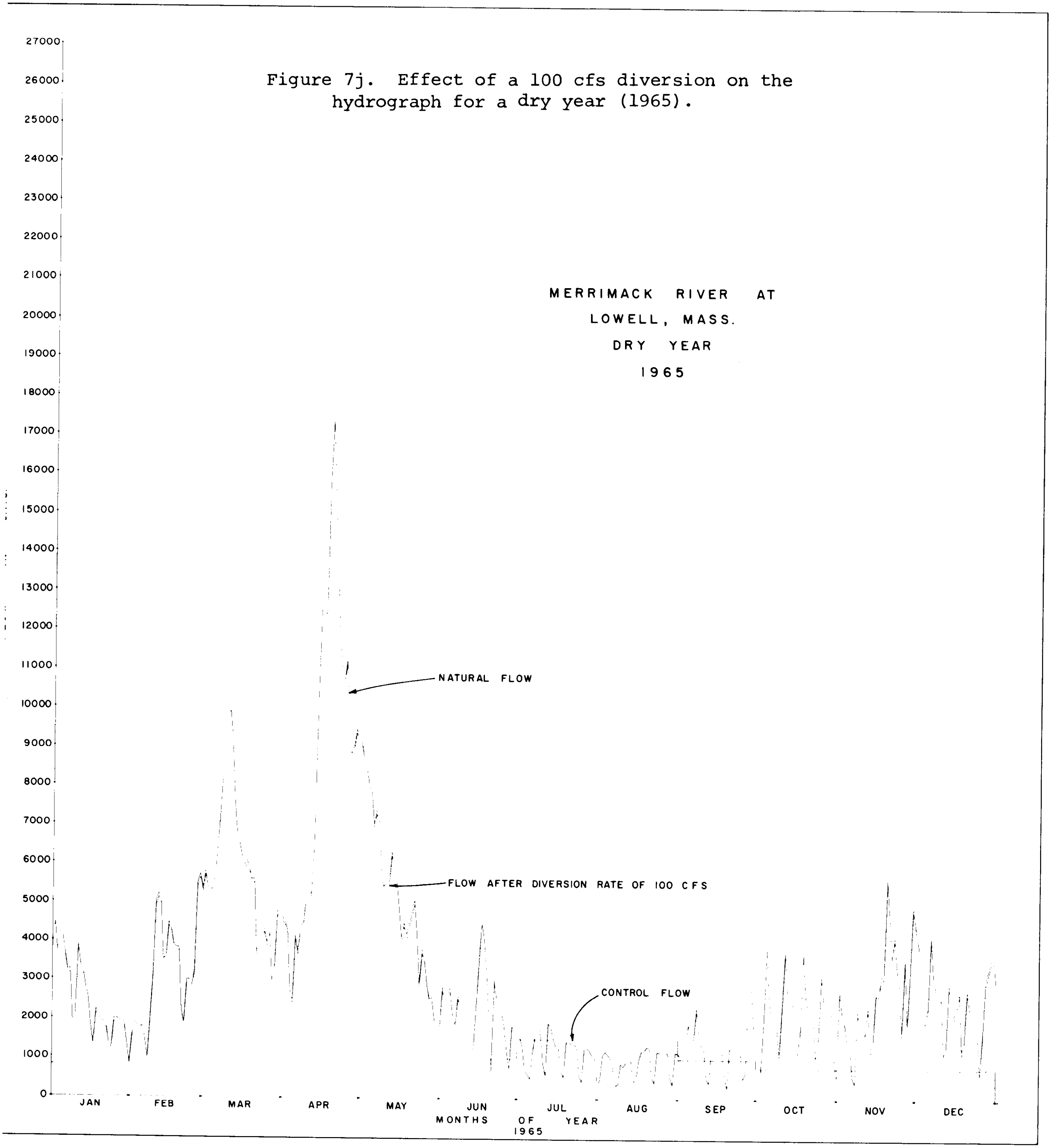


Figure 7k. Effect of a 500 cfs diversion on the hydrograph for a dry year (1965).

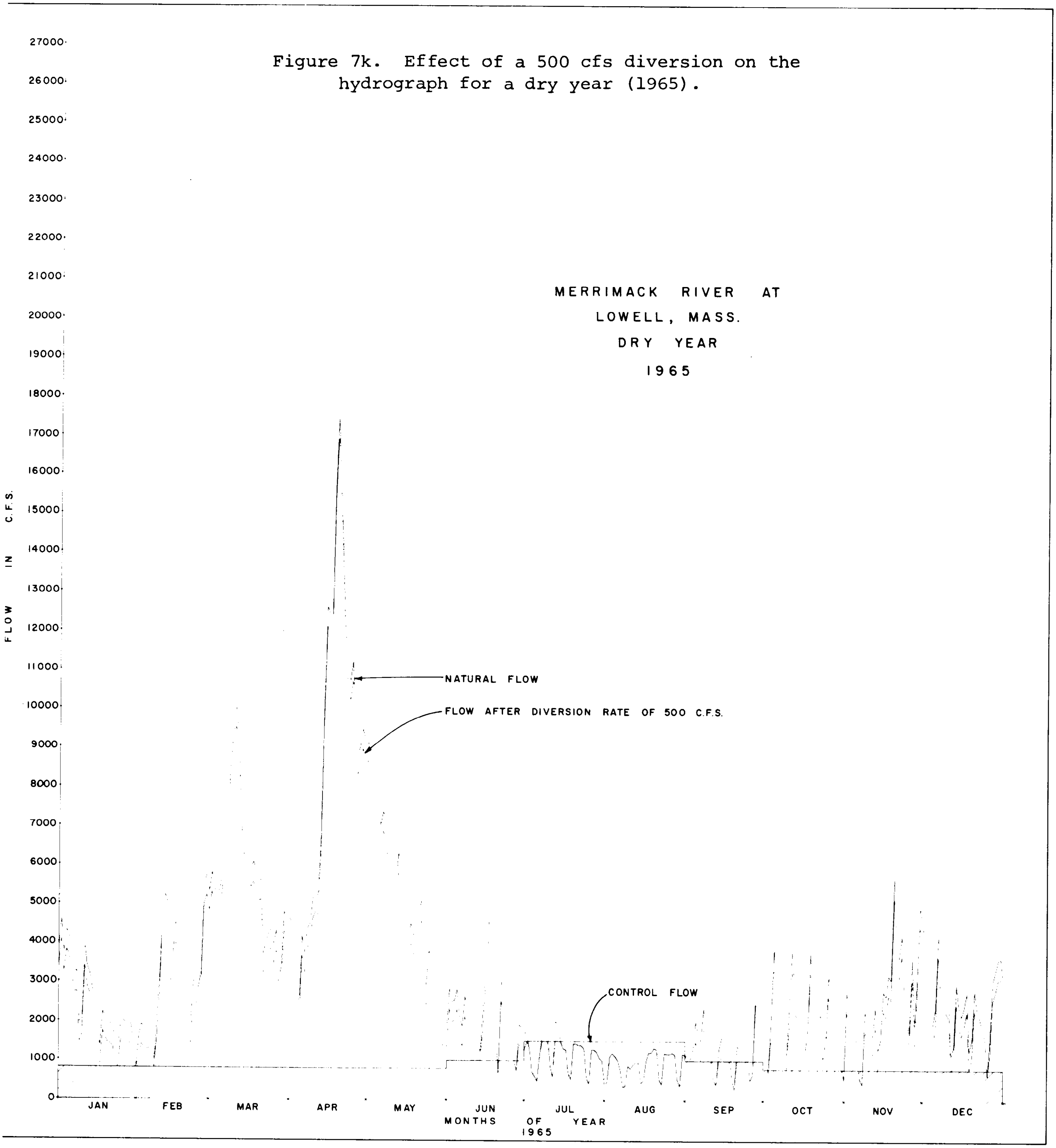


Figure 71. Effect of a 1,100 cfs diversion on the hydrograph for a dry year (1965).

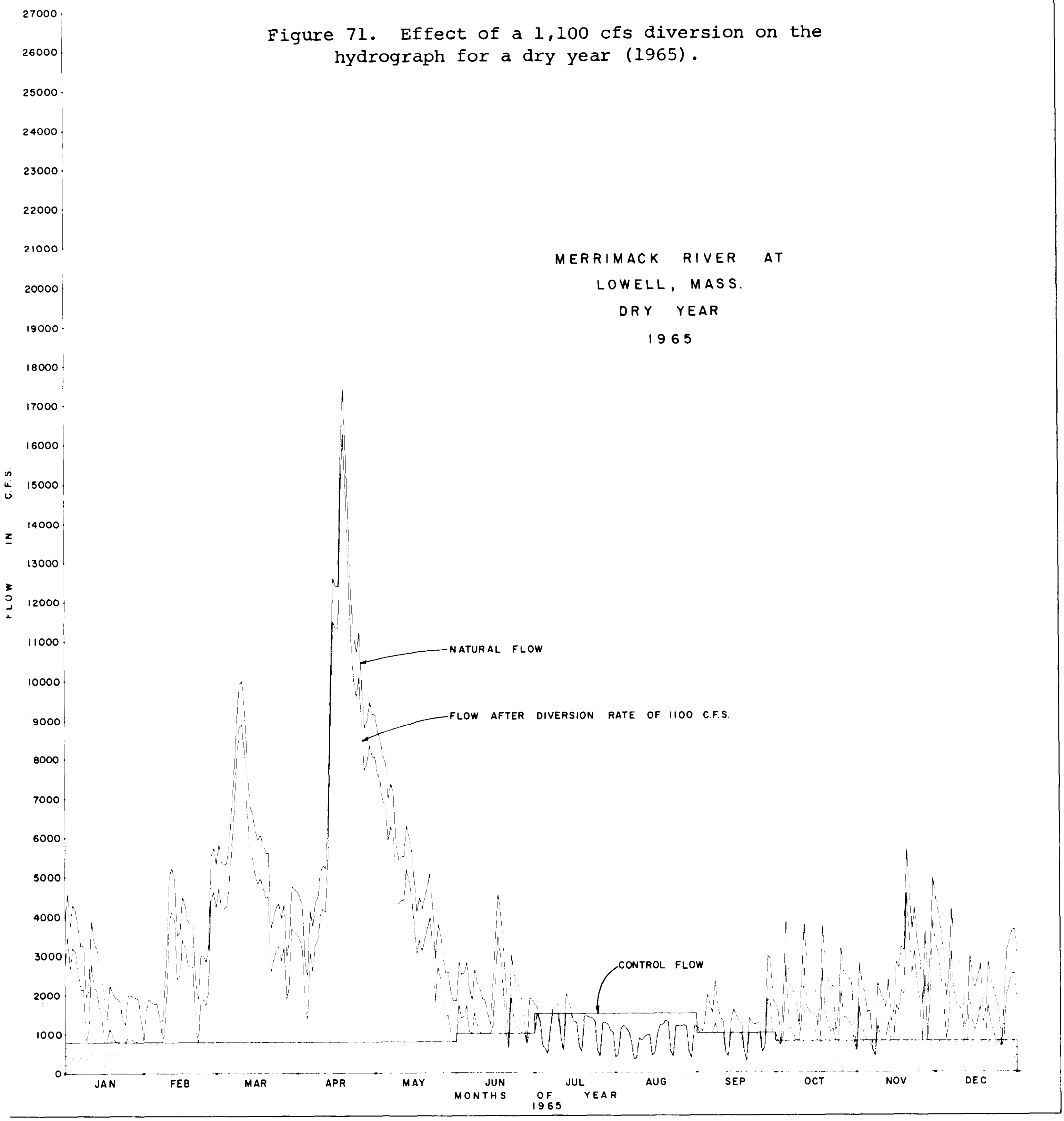
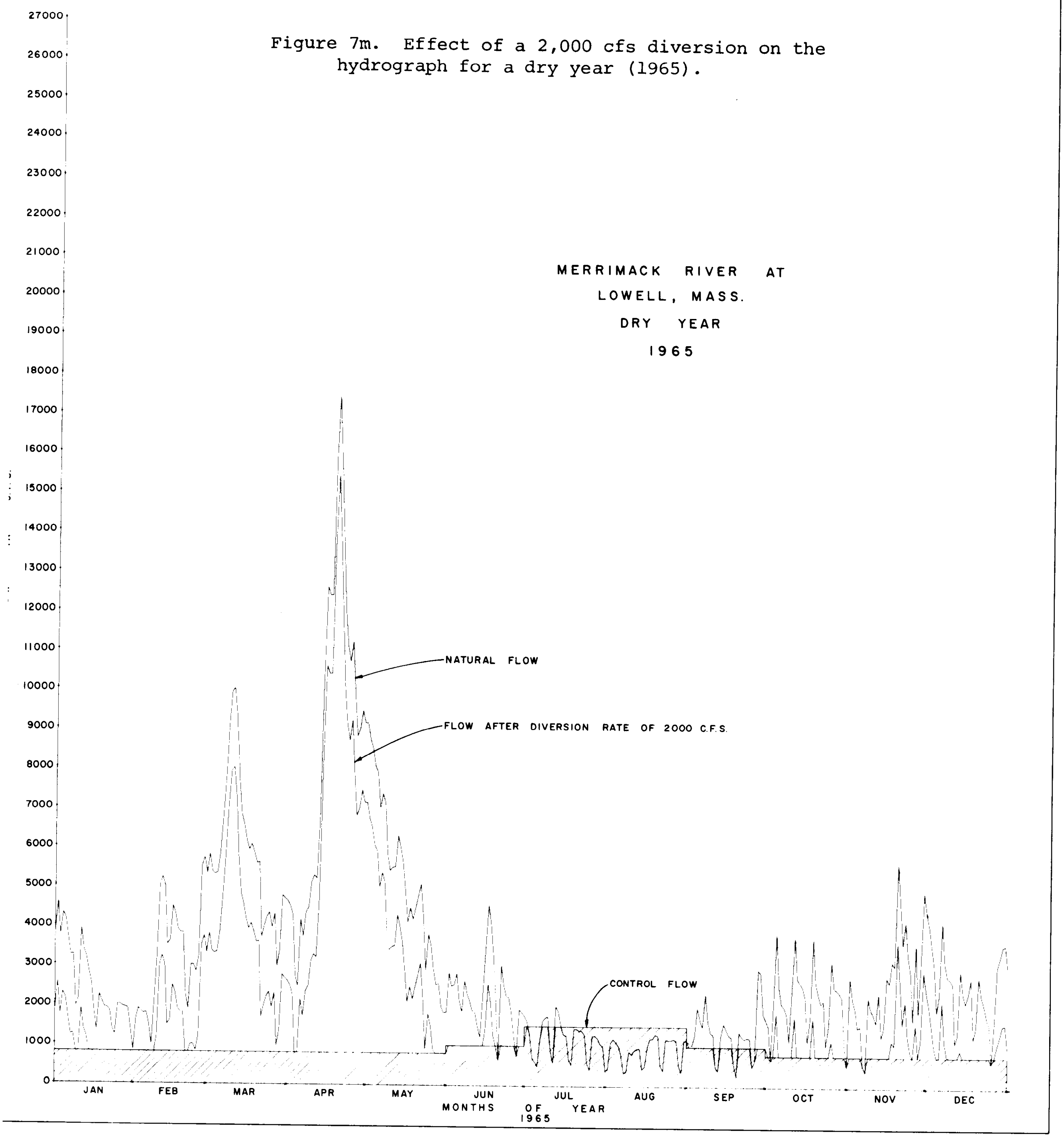


Figure 7m. Effect of a 2,000 cfs diversion on the hydrograph for a dry year (1965).



as suggested by the Corps of Engineers are shown in Figure 7a, which is based on average weekly flows in the Merrimack River over the period of record. Figures 7b through 7m are included in order that the reader may gain an appreciation of the wide range of flow conditions which occur from year to year, and how diversions may affect the hydrograph in each of the cases presented. Table IV illustrates the distribution of flow rates in the Merrimack River over the period of record.

Referring now to 7a, on the average, water flow exceeds the control value for each month by an amount which is equal to the differential between the control zone (shaded) and curve "A". If we then impose some suggested diversion rates on curve "A", we can study the overall relationships between absolute and relative flow patterns over the course of the year, and gain some knowledge as to the average amount of time certain parts of the river would be exposed to measureable salinities. For example, the increased amounts of time during which flow rates would be 5,000 cfs or less are:

0.5 weeks at diversion rate "B";
1.5 weeks at diversion rate "C";
12.0 weeks at diversion rate "D"; and
19.0 weeks at diversion rate "E".

Putting this in terms of salinity exposure, using high tide (Figure A-18 of Appendix A), Station S-5 (Km 12 of VAST) would experience salinities at least as high as 19.5 $^{o}/oo$, 3 percent, 8 percent, 62 percent, and 100 percent more of the time than at present. At the mouth of the river (Figure 3), high tide salinities would approach 29.5 $^{o}/oo$ for equally

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TABLE IV.

FLOWS IN CFS WHICH WERE EXCEED IN A GIVEN PERCENT OF TIME DURING THE PERIOD OF RECORD (1927 - 1968)

MONTH	MAXIMUM FLOW	PERCENT 02%	05%	10%	20%	50%	80%	MINIMUM FLOW
1	39800.	20200.	14900.	11900.	8600.	5410.	3330.	585.
2	27200.	16600.	14300.	11600.	8840.	5600.	3600.	630.
3	161000.	41800.	29400.	21600.	15600.	9540.	5930.	1410.
4	77200.	45200.	36900.	31200.	25900.	16900.	10700.	2490.
5	48600.	29900.	23600.	19900.	16300.	9660.	6060.	666.
6	47800.	19600.	14500.	11900.	8960.	4680.	2780.	403.
7	27900.	9420.	7260.	5520.	4260.	2660.	1600.	249.
8	20600.	8000.	6020.	4580.	3280.	2100.	1310.	233.
9	118000.	15600.	7930.	5120.	3730.	2040.	1280.	219.
10	34900.	13000.	8510.	6660.	4810.	2550.	1430.	214.
11	66200.	22800.	15900.	12100.	8180.	4350.	2460.	319.
12	39800.	24600.	17400.	13500.	9150.	5140.	3050.	378.

lengthened periods of time, and low tide salinities of 22.5 ^{o}/oo would also occur more often. Intuitively, this sort of pattern would be expected to hold true for any station, but would be proportionately different depending upon flow.

Seasonal changes in longitudinal salinity distribution beyond mile 5 of the estuary are schematically illustrated in Figure 8 through 10. Detectable salinities of 5 ^{o}/oo were used in these figures, and upstream intrusions are based on average monthly flow rates from 1927-1967. It should be noted that in Figure 10 (September) intrusions occurring at diversion rates "D" and "E" (-1,100 cfs and -2,000 cfs, respectively) are hypothetical cases since no diversions will be made to cause flows to be reduced below control levels.

The figures provide an indication of how far upriver a salinity gradient of 5 ^{o}/oo will move each season, given that flow conditions approximate the 40 year mean used in our calculations. The difference in salinity encroachment between average natural weekly flows and the highest diversion rate considered (E) varied from 0.47 miles (0.76 Km) in March and May, when flows are high, to 1.71 miles (2.75 Km) in September and October. However, salinity intrusion characterizing monthly averages of daily flow minima for each month are generally of the same magnitude as the maximum diversion rate. Therefore, organisms at most locations would simply be subject to more frequent increases in salinity. Salinity encroachment at control levels is considerably

A. Avg. Natural Flow 1927-1967
B. -100 cfs
C. -500 cfs
D. -1100 cfs
E. -2000 cfs
F. Monthly avg. of daily min. 1926-1969
G. Control levels

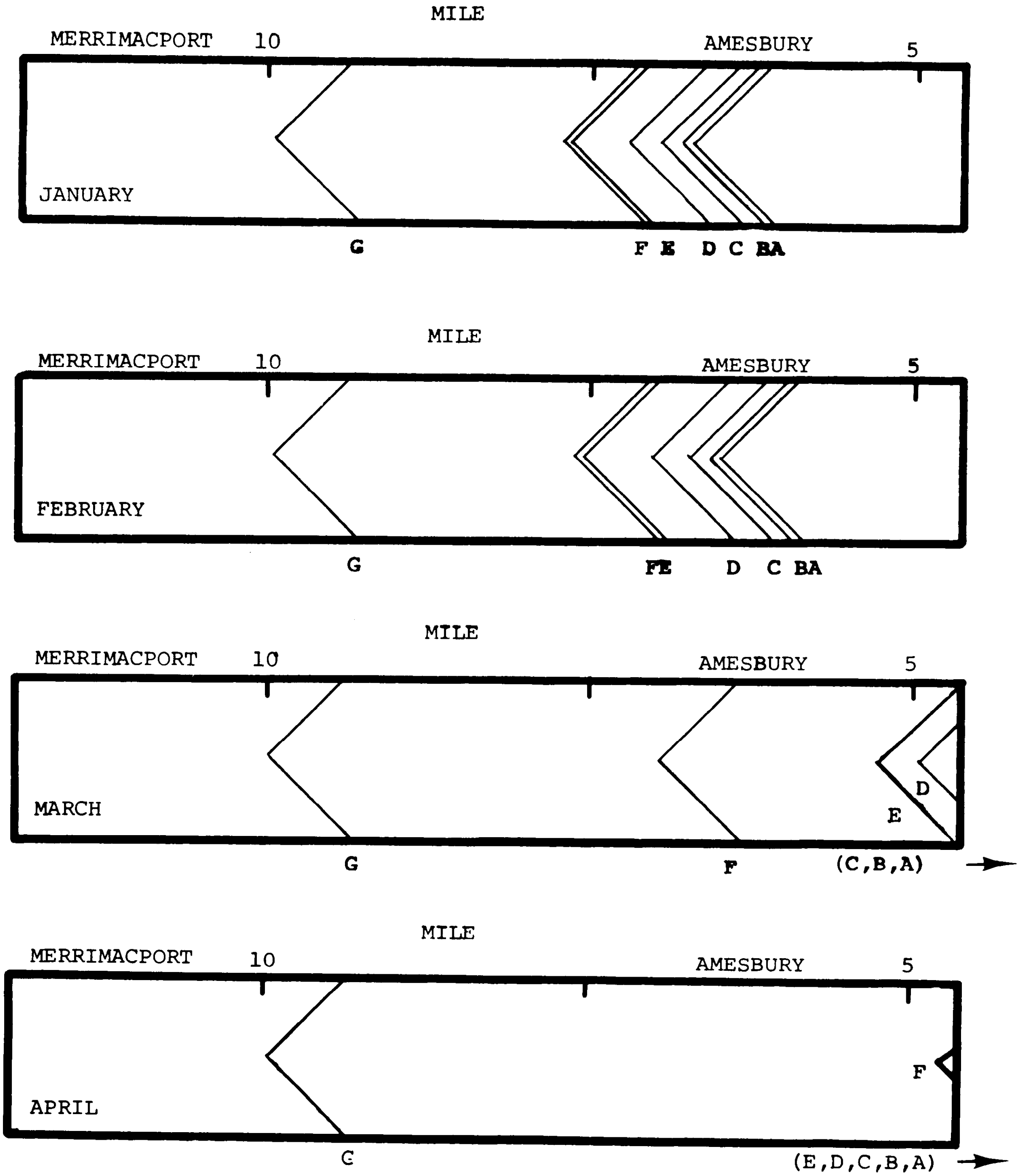


Figure 8. Average longitudinal intrusion of waters of 5 ‰ at different rates of diversion during high tide.

A. Avg. Natural Flow 1927-1967
B. -100 cfs
C. -500 cfs
D. -1100 cfs
E. -2000 cfs
F. Monthly avg. of daily min. 1926-1969
G. Control levels

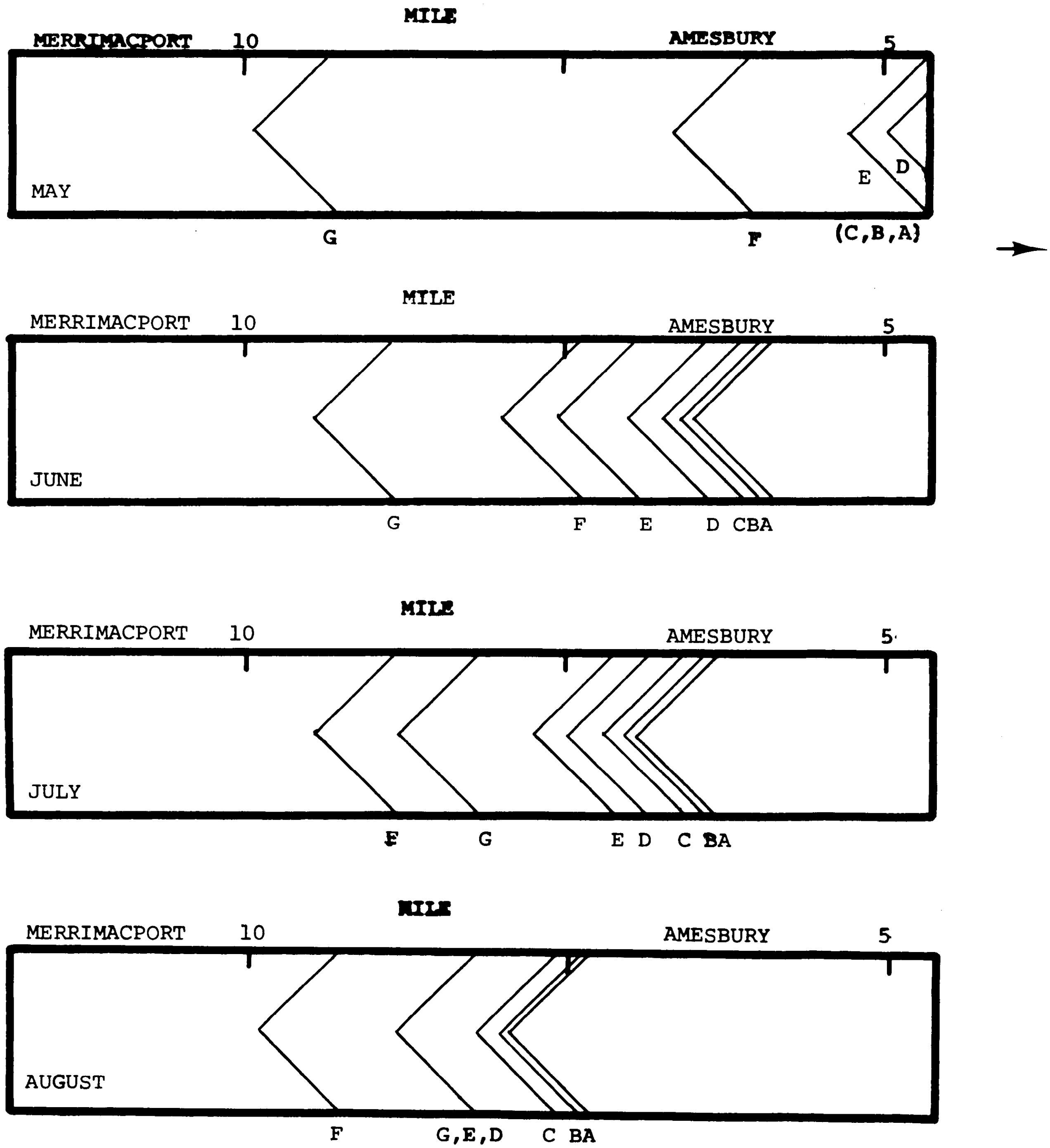


Figure 9. Average longitudinal intrusion of waters of 5 $^{o}/oo$ at different rates of diversion during high tide.

A. Avg. Natural Flow 1927-1967
B. -100 cfs
C. -500 cfs
D. -1100 cfs
E. -2000 cfs
F. Monthly avg. of daily minima 1926-1969
G. Control levels

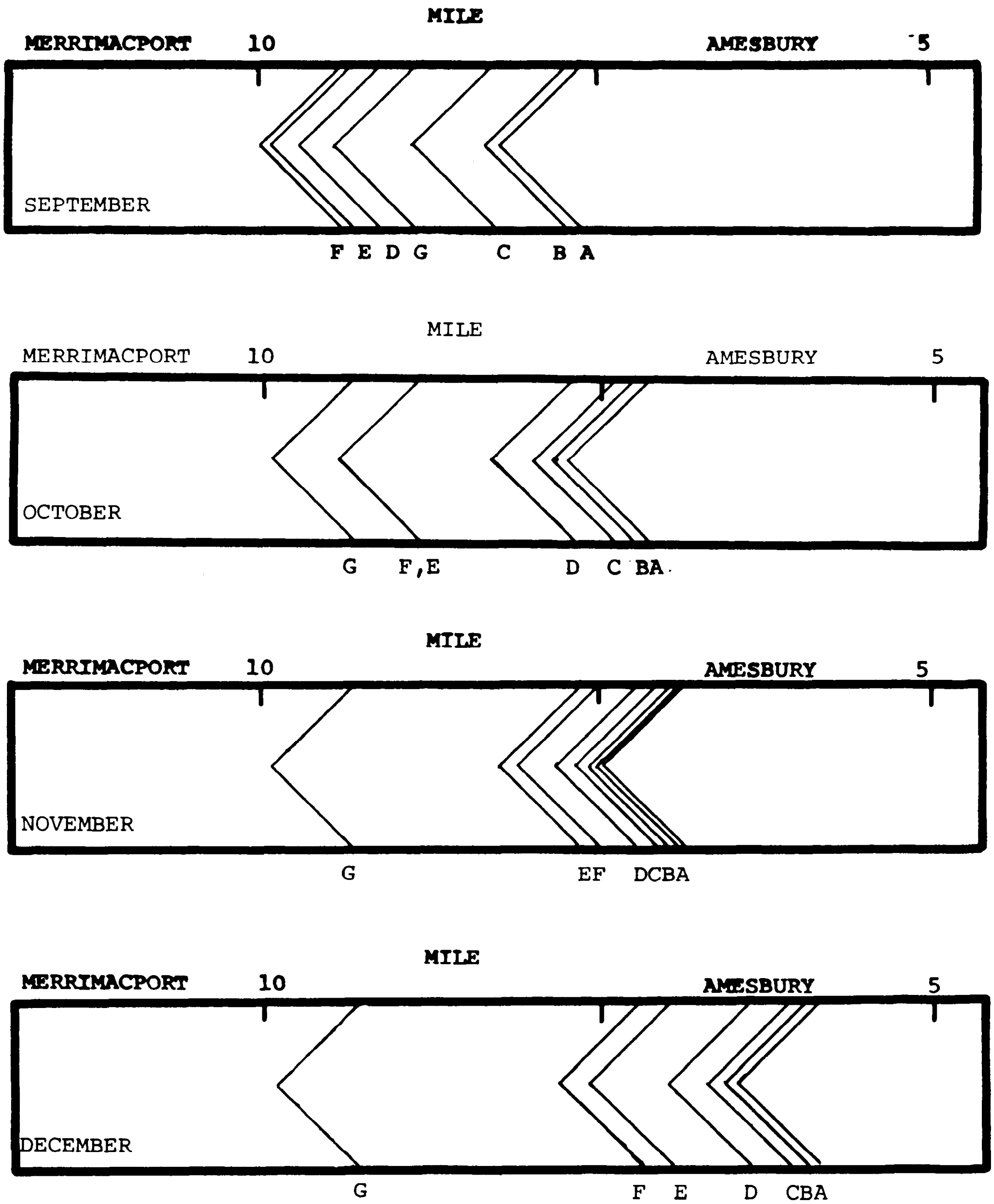


Figure 10. Average longitudinal intrusion of waters of 5 $^{o}/oo$ at different rates of diversion during high tide.

higher, in proportionate sense, than the 2,000 cfs diversion rate (excepting the summer and fall months). This amounts to from 2 (3.22 Km) to > 5 miles further upriver than that which occurs under average condtions, depending upon season. Diversions representing smaller proportions of the natural flows, for example, 1,100 cfs from 16,000 cfs, move the point of minimum measureable salinity lesser distances upstream, in this instance three tenths of a mile (one-half kilometer).

Beyond these seasonal patterns, tidal oscillations produce interesting results also. A six hour tidal cycle moves the salinity concentration pattern approximately 7 to 8 Km (4.34 to 4.96 miles) up or downstream. Depending on the grid point this movement causes varying degrees of six hour salinity fluctuations. For instance, at grid point 9, under an 800 cfs condition, salinity varies from 0 to 6 ^{o}/oo. At point 35, with 16,000 cfs, salinity varies from 0 to 11.5 ^{o}/oo.

C. ALTERATIONS OF ESTUARINE CIRCULATION

The Merrimack River Estuary usually exhibits the characteristics of the moderately stratified estuary (type B) in the estuarine sequence as defined by Pritchard (1959, 1968). Salinity distribution in the Merrimack River varies as a function of river flow and phase of the tide. As in most moderately stratified estuaries, the effects of the earth's rotation are discernable. The tidal flat region bordering the southern bank of the Merrimack River Estuary near its mouth is characterized by water of lower salinity than the water of the main channel. As has been described in pages III-17 through III-18, and summarized on pages III-18 and III-21, the model treats the average salinity along the main channel of the estuary where the longitudinal salinity gradients are most important and the effect of the earth's rotation has therefore been neglected.

Vertical stratification in the Merrimack Estuary varies with river flow. Hartwell (1970) has shown that stratification occurs in the estuary when river flows are in the range of 1,900 to 6,300 cfs, but it is generally observed that the estuary exhibits well developed stratification at river flows above 3,000 cfs. As flows drop below this value the estuary becomes progressively less stratified and increasingly well-mixed.

Complete records on Merrimack River daily flows have been taken at the Lowell Gauging Station from 1923 to the present. A study of the data from 1923 to 1968 (Table V) indicates that monthly river flows in July, August, September, and October have been below 6,000 cfs at least 85% of the years on record, and dropped below 3,000 cfs in at least 50% of the years. In addition, monthly flows in November, December, January, and June are below 6,000 cfs in more than 50% of the years. Because alterations in estuarine circulation patterns occurring in this range of flows may affect other physical parameters discussed later, and because such flows are frequently approached in the Merrimack River, diversions which would increase these periods of time substantially may have important ecological implications.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

TABLE V.

NUMBER OF TIMES RIVER DISCHARGE WAS AT OR NEAR

DESTRATIFICATION LEVELS (1923-1968)

DISCHARGE (cfs)	(1923-1968) MONTHS											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Under 3,000 cfs	7	3	0	0	0	7	28	37	34	24	9	7
3,000 cfs to 6,000 cfs	14	23	4	0	3	20	14	6	10	15	19	18

D. PHYSICAL CHANGES RESULTING FROM ALTERATIONS OF CIRCULATION

1. Alterations in Suspended Sediment Distribution:

Ocean water entering the estuary carries a relatively small suspended sediment load, while the river, even under periods of low discharge, carries a much higher load. Because of this difference in sediment content of the two masses of water, changes in the freshwater/saltwater stratification of the estuary could lead to alterations in the pattern of sedimentation.

When the river is at high discharge, much of the sediment load is flushed out of the estuary over the salt wedge, and little sedimentation occurs (Goldsmith, 1971, pers. comm.). Under periods of normal river flow, but when stratification is still well-developed, large amounts of sediment are deposited over shallow areas on the south side of the estuary. This heavy sedimentation is particularly apparent on Joppa Flats, where accumulation of sediments and pollutant materials contributed to the recent shoaling of the channel south of Woodbridge Island, and also the rapid accretion of *Spartina alterniflora* marsh (Hartwell, 1970).

The pattern of sedimentation becomes quite different however under low flow periods when the estuary is unstratified. At these times sediments do not settle selectively over Joppa Flats, but are more or less evenly deposited throughout the estuary.

Diversion of freshwater from the vicinity of Lowell, Massachusetts may affect the present patterns of sedimentation in two ways. The removal of freshwater would reduce the amount of sediment carried by the river, which will in turn lower the total load brought into the estuary. However, with decreased discharge less of this river water will be flushed out, possibly resulting in a net increase in the amount of fine sediment deposited within the estuary (Goldsmith, 1971, pers. comm.). Since diversion of freshwater will increase the number of days on which flows are low, this should lead to reduced deposition over the Joppa Flats area but somewhat increased sedimentation in other parts of the estuary. The extent of these changes and their significance cannot be determined without further study.

2. Net Inflow of Bottom Sediments Resulting From Changes in Current Flow:

Hartwell (1970) and Hayes, et al (1970) have done a considerable amount of research on hydrography and sedimentation in the Merrimack River Estuary and other estuaries. This research has shown that velocities of currents entering an estuary on the flood tide tend to be considerably stronger than those of currents leaving on the ebb, and these currents are active in the formation of flood tidal deltas due to a net influx of sediments into the estuary.

Aerial photographs of the Merrimack River Estuary taken in July 1971 reveal sand movements along the bottom and into the estuary at its narrow entrance. This transport has resulted in the production of a large bedform with steep slip-faces located on the inshore side. In spite of this observed influx of sand, the flood tidal delta at present is relatively small in comparison to the total size of the estuary, and with respect to flood tidal deltas in other estuaries. In addition, indications are that the Merrimack River flood delta has been relatively stable, with only minor changes compared to other estuaries.

How might this situation change as a result of diversion? Hayes, et al (1970) have shown that the velocity, time during which flood tidal currents dominate, and distance of penetration of the salt wedge are all directly related. Their studies have also shown that decreased river discharge results in an increased penetration of the salt wedge. Therefore, since the amount of sand transported into the estuary is related to the amount of penetration of the salt wedge (Hartwell, 1970), it follows that an increase in the amount of flood oriented sand waves will occur with decreased discharge.

Goldsmith (1971, pers. comm.) suggested that the following sequence may be theoretically possible with decreased river discharge:

a) An increased rate of sediment movement, as bedforms, into the estuary through the flood tidal channel resulting in a larger flood tidal delta;

b) Increased sand deposition which would require increased effort of the existing maintenance dredging program; and

c) Decreased circulation in the Merrimack River Estuary resulting in increased deposition of fine sediments (and associated pollutants) in the estuary.

Even a small increase in rate of sediment influx into the Merrimack River could result in rearrangement of ebb and flood tidal channels, rearrangement of circulation patterns within the estuary, and altered patterns of erosion and deposition within the estuary. Hartwell (1970), found very strong sediment patterns within the estuary, and these could conceivably be changed, thus affecting the distribution of infauna such as clams. Increased sand deposition at the river entrance (Point "b" above) is thought not to be a major issue since the Army Corps of Engineers periodically dredges this area. Over the past ten years the Corps has removed a total of 700,000 cubic yards of sediment from the mouth of the Merrimack River. This was accomplished in five dredges, at approximately two year intervals, and an average removal of 140,000 cubic yards per dredging effort. It is expected that this activity will continue at essentially the same rates as in the past.

It is reasonable to assume that much of the sand transported into the estuary with greater salt-wedge penetration will come from the beaches adjacent to the inlet. A model of tidal circulation at inlets based upon studies of 15 New England (including the Merrimack) and numerous Alaskan coastal inlets showed that flood tidal currents tend to approach from the sides of an inlet and along the beaches (Hayes, _et al_, 1970). Based on these findings, increased transport into the estuary could result in possible beach erosion adjacent to the jetties.

E. UPPER ESTUARINE TEMPERATURE CHANGES

Daily and seasonal temperature variability is generally more pronounced in river than in ocean waters, with summer temperatures generally warmer, and winter temperatures colder, than the ocean. This implies that temperature variability in an estuary is directly affected by the amount of freshwater entering that estuary.

A reduction in freshwater from any proposed upriver diversion could result in two noticeable changes in the temperature characteristics of an estuarine system. If significant quantities of water are withdrawn during the summer when flows are normally low, stagnant pools of water could form. These would be subject to excessive heating, and could affect the ecology of certain portions of the estuary. Since no temperature studies have been done on this region, the extent of thermal increase cannot presently be determined.

A lesser, but still noticeable effect may be observed in the lower estuary where reduced freshwater inflow could reduce daily and seasonal temperature fluctuation in the mixed estuarine waters, making them conform more closely with ocean temperature variabilities.

F. CHANGES IN THE EFFECT OF POLLUTION LOAD

The Merrimack River is grossly polluted along most of its length by industrial and domestic effluents. Numerous studies have been done to determine the nature and extent of this pollution, including work done by Oldaker (1966) and Daly, et al (1969). Data from these reports indicate that many parts of the freshwater river become anaerobic, especially in late summer and early fall when flows drop and temperatures rise. The situation is not nearly as serious in the Merrimack River Estuary, for the pollution load soon becomes well-mixed with relatively unpolluted ocean water. Even so, Jerome, et al (1965) found late summer dissolved oxygen readings as low as 5.0 ppm at the upper stations in 1964, and indicated that readings as low as 1.0 ppm have been observed at these stations during other years. They conclude that dissolved oxygen readings lower than 5.0 ppm will have adverse effects on finfish and some invertebrates, especially during the warmer summer months.

Since DO readings presently drop to critical levels under low flow/high temperature conditions in late summer and early fall, it is probable that unless pollution is abated, extensive diversion during this time period may further aggravate the situation. However, since the control flows specified for these months would not permit diversion when the flows are below 1,000 cfs for June and September, and 1,500 cfs for July and August, no serious problems are anticipated.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

V. POTENTIAL BIOLOGICAL CHANGES RESULTING FROM DIVERSION

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

V. POTENTIAL BIOLOGICAL CHANGES RESULTING FROM DIVERSION

A. INTRODUCTION

Every physical change brought about in an ecological system will result in corresponding changes in the biology of that system. These changes will be manifested by alterations in aspects of life history of individual organisms, which in turn may affect the distribution and abundance of entire populations. Many of these biological changes may be imperceptible, and will fall well within the naturally occurring limits of variability experienced by a species. However, others may place sufficient stress upon a species so that survival rates could decrease, resulting in a gradual elimination of this species from a formerly suitable habitat. The interrelationships of the several populations occurring in an ecosystem are both complex, and for some, critical. Loss of an important population could result in a significant change in the makeup of the biotic community.

It must be understood that the limited data available do not permit any definite conclusions to be drawn relative to the biological effects of diversion on the intricate ecological balance of the estuary. However, from past experience, the reaction of specific organisms to physical changes can be predicted, and the extent of possible changes can be discussed. For the present limited study, the following approaches to the problem have been used. Field sampling was carried out for five biological components of the estuarine system (intertidal benthos, intertidal algae, intertidal vascular plants, subtidal benthos, and plankton). Using the results of field sampling and available literature, an attempt has been made to cover, whenever possible, the following format for each biological component:

1) General introduction to the study, including purpose;
2) Methods utilized in collection of samples and analysis of data;
3) What is the existing distribution of the species and are these species marine, estuarine, cosmopolitan, or freshwater?;
4) What are the dominant species in the biological association at each station?;
5) What part of the life cycle of dominant species will be most affected by a salinity increase or by the potential changes in other physical parameters mentioned above? At what time of year is this situation most critical?
6) How might the biological association change if the salinity is increased, or if any of the other projected physical changes occur?;
7) Will this change in the association lead to other biological or physical changes?

8) Will new species be introduced into the area if salinity is increased, or if other physical changes occur, will any species be eliminated?

Species of commercial, recreational, or aesthetic importance to the Merrimack River Estuary have been discussed individually, and based on field sampling and available literature, an attempt has been made to evaluate the economic importance of the species to the area, the pertient aspects of life history, present distribution of the species in the Merrimack River Estuary, and potential effects of diversion on the ecology of the species.

B. INTERTIDAL BENTHIC ORGANISMS

1. Rationale and Objectives:

If we are to make sound predictions concerning the biological effects of flow diversion on the ecology of the Merrimack River Estuary, it is essential to have a detailed picture of the animals and plants presently inhabiting the intertidal zone. This is particularly important because many of these organisms are extremely sensitive to changes in physico-chemical factors that occur in this environment, such as exposure to wave action, fluctuating salinity and temperature, and desiccation. Therefore, these organisms can tell us more about the existing physical conditions in the estuary and any changes that may occur following diversion than we could learn through our efforts due to the lack of sensitivity of sampling instrumentation. In addition, the wide variety of substrata in the intertidal, including mud, sand, marsh, and rocks, provides an assortment of micro-habitats, and thus potentially allows colonization by a series of introduced species should the physico-chemical changes resulting from diversion provide optimal conditions. Because an introduction of species could lead to interspecific competition, it is important to attempt to predict those species that may be introduced, those that could be eliminated as a result of competition or physiological stress, and how these floral and faunal changes may affect the overall composition of the intertidal community.

The objectives of the studies were threefold: 1) to collect and identify the intertidal algae, vascular plants, and invertebrates present at selected sites throughout the estuary; 2) to provide a qualitative description of the intertidal biota from the open ocean to the upriver limits of salt water intrusion; and 3) to evaluate the potential effects of freshwater diversion on this biota.

2. Description of Stations:

A complete description of all intertidal stations sampled is presented in Table VI. The breakwater at Stations 1 and 3 provided the maximum amount of stable substrata for epibenthic organisms. The intertidal areas at the remaining stations were primarily composed of scattered rock outcrops, boulders, pebbles and junk, interspersed with sand or mud. The largest amount of solid rock was usually evident in the upper intertidal and the substrata tended to grade into sand-mud in the lower shore. From the mouth of the river to Station 29 there was a reduction in the amount of rocks (particularly large outcrops) and a progressive increase in the deposition of mud on the shore. A buildup of extensive peat-like material was evident in the upper intertidal zone at many stations throughout the estuary, where the roots of *Spartina* spp. stabilize muddy surfaces and allow colonization by seaweeds, vascular plants and invertebrates.

TABLE VI

A DESCRIPTION OF THE INTERTIDAL COLLECTING STATIONS

STUDIED IN THE MERRIMACK RIVER ESTUARY

STATION	LOCATION AND DESCRIPTION
1	Open ocean side of the breakwater at Salisbury Beach: At this location large granite boulders extend from a sloping sand beach out into the clear, cold waters of the Atlantic. The rocks are exposed to open ocean surf, and those immediately adjacent to the beach are scoured clean by constant abrasion. A lush covering of marine algae and extensive sets of blue mussels and barnacles cover the intertidal and subtidal zones.
2	Estuarine side of the breakwater at Plum Island Point: This area consists of an extensive sand and gravel beach studded with large granite boulders. Currents are extremely strong, waves hit the area constantly, and the rocks are fairly well scoured. Marine organisms are only found in cracks in the rocks were they are protected from abrasion.
3	Estuarine side of the breakwater at Salisbury Beach: At this station large granite blocks are surrounded by the sands of Salisbury Beach. The rocks are exposed to very strong tidal currents and choppy waves. The overall appearance of the area is considerably sparser than Station 1, but mats of green algae cover the intertidal, and fairly large beds of blue mussels are found at low water.
4	Breakwater near Badgers Rocks: A breakwater of large granite rocks extend from the intertidal area out into deeper subtidal waters at this location. Coarse sand and gravel surround the rocks, which are covered by barnacles above mean water, and large

TABLE V I (continued)

STATION	LOCATION AND DESCRIPTION
4 (con't)	sets of blue mussel and mats of filamentous green algae at low water.
5	Western bank of Plum Island River underneath the bridge connecting Plum Island to Newburyport: This habitat, a combination of mud banks and outcroppings of small granite rocks, is located on the Plum Island River, a tidal channel connecting the Parker River - Plum Island Sound Estuary with the Merrimack River Estuary. Beds of _Spartina_ spp. predominate on the flats, and the rocks, all of which are coated with green filamentous algae, hold small colonies of barnacles and blue mussels.
6	Black Rock Point: This habitat consists of a large outcropping of rocks located throughout the intertidal and subtidal zones, surrounded by tidal creeks, mud flats, and beds of _Spartina_ spp. The rocks throughout the intertidal are covered with thick mats of _Ascophyllum_ and _Fucus_, and the flats, while high in H_2S, support a dense population of the soft-shell clam, _Mya arenaria_.
7	Lunt Rock: Lunt Rock is a large granite boulder lying in the shallow subtidal flats. The top of the rock is exposed at low tide, and is covered by an extensive set of barnacles and blue mussels.
8	Morrill Creek: This habitat consists of a series of large granite rocks surrounded by an extensive soft-shell clam flat. The rocks are coated with silt and mud, and support few intertidal organisms.

TABLE VI (continued)

STATION	LOCATION AND DESCRIPTION
9	Joppa Flat: Joppa Flat is an extensive shallow mud flat located on the Newburyport side of the Merrimack River Estuary. No rocks are exposed in this area, and the shallow sludge covered bottom supports large beds of blue mussels and clams.
10	Rocks just upriver from Coffin Point: This area is characterized by salt marsh interspersed with granite outcroppings. Wave action and currents are minor, water looks and smells polluted, and few organisms are visible on the sludge-covered rocks.
11	Waterfront at Newburyport just west of the power generating station: This habitat consists of slime covered wooden pilings. No living macroinvertebrates are apparent, but the sight and smell of pollution is impressive.
12	Salisbury shoreline just upriver of the Rt. 1A Bridge: This area is predominantly a large <u>Spartina</u> spp. covered mud flat. The mud is soft and high in H_2S, and the whole area emits a strong rotten smell. Clusters of slime-covered rocks jut out at points throughout the intertidal.
13	Shoreline across the river from Station 12: This habitat is a sloping gravel beach cluttered with rocks and junk. Several relatively clear freshwater springs percolate out of the sand and enter the river. With the exception of a coating of blue-green algae, the habitat is bare of intertidal organisms.
14	Twin Rocks station, on the Salisbury side of the river: This habitat is composed of a mixture of rock outcroppings and mud, interspersed with small patches of

TABLE VI (continued)

STATION	LOCATION AND DESCRIPTION
14 (con't)	*Spartina* spp. H_2S is just beneath the surface of the mud, water is brown and putrid, and little life other than blue-green algal scum is visible on the rocks.
15	North End Boat Club: A sloping shore composed of rocks, pebbles, and patches of *Spartina* spp. predominate in this area. All rocks are coated with blue-green algal scum, and little life is visible.
16	Station in the secondary tidal channel across from Ram Island, near Town Creek: This habitat consists of *Spartina* spp. flats at the upper intertidal, blue-green algal covered rocks in the intertidal, and mud at and below LW. H_2S is near the surface of the mud throughout the area, and wave and current action are minimal.
17	Rocky shore across from Ram and Carr Islands: This habitat is primarily a large pile of rocks extending out into a fairly rapid channel. The rocks are barren except for a coating of blue-green algae.
18	Station on the rocky promontory of Ram Island: This station consists of blue-green algal covered rocks outcropping from *Spartina* spp. beds near HW and mud flats at and below LW.
19	Station in the main channel on a rocky promintory of Carr Island: As with the previous station, the habitat is a combination of rock outcroppings surrounded by mud flats and upper intertidal *Spartina* spp. beds. All rocks are covered by a thick scum of blue-green algae.

TABLE V_I (continued)

STATION	LOCATION AND DESCRIPTION
20	Station on the north side of the river across from Eagle Island: This habitat is composed of a series of rocky outcroppings throughout the intertidal, interspersed with anoxic mud flats and <u>Spartina</u> spp. beds. The <u>Spartina</u> spp. appeared rather unhealthy, and only a light coating of algae covered the rocks.
21	Rocky shore on the Newburyport side of Deer Island: This station, located at the base of the bridge, is composed of rocks in the intertidal, with patches of <u>Spartina</u> spp. near high tide mark. The rocks are lightly coated with blue-green algae, and H_2S is close to the surface in the mud.
22	On the south shore just upriver of the Rt. I-95 Bridge: This habitat is mostly sloping rocky substratum interspersed with some mud and gravel. Patches of <u>Spartina</u> spp. cover the upper-intertidal, and a light coating of blue-green algae covers some rocks.
23	Rocky promontory at Salisbury Point: This habitat, located in a cove at the bend of the river, is composed of rock outcroppings and scattered broken rocks throughout the intertidal, with gravel and some <u>Spartina</u> spp. in mud near high tide.
24	Shoreline in Amesbury between Stations 23 and the Allen B. Marina: This area is characterized by very anoxic and putrified mud, interspersed with junk. H_2S predominates and the few rocks present are coated with muck and mud.
25	Allen B. Marina: A mixture of scattered rocks, sand and mud characterize this area. H_2S is just below the surface in mud, all

TABLE VI (continued)

STATION	LOCATION AND DESCRIPTION
25 (con't)	rocks are coated with scum, and raw sewage often covers the banks. Some *Spartina* spp. is present in the intertidal, interspersed with freshwater reeds.
26	On the north shore just upriver of the factories: This habitat is a rocky conglomerate shore, gently sloping into muddy water. A mixture of *Spartina* spp. and reeds is scattered on the beach.
27	On the north shore just upriver of the Seahorse Marina: A mixture of conglomerate and mud similar to Station 26 is found at this location.
28	On the south shore just downriver of the Artichoke River: A very gently sloping mud habitat, covered by a thick mat of freshwater reeds, is found at this location.
29	On the south shore between the Artichoke and Indian Rivers: This habitat is an all mud flat covered by a dense thicket of freshwater reeds and grasses.
30	North shore one-half mile upriver of Locust Street: This habitat is characterized by a mixture of scattered rocks gently sloping to the water, interspersed with gravel, sand, and mud. Freshwater plants predominate in the muddy areas.
31	South shore just upriver of the Groveland Bridge: This station is a typical freshwater habitat composed of scattered rocks and mud, and covered with a wide variety of freshwater plants.

3. Intertidal Algae and Vascular Plants:

Methods:

Collections and observations of intertidal algal and vascular plants were made throughout the Merrimack River Estuary during the summer and fall of 1971. Vascular plants were studied at 14 stations and algae was studied at 13 locations (Figure 11). Representative specimens of algae from each site were collected, processed as herbarium voucher specimens and deposited in the Herbarium of the University of New Hampshire (NHA). A deliberate attempt was made to summarize a broad "baseline" of information on species composition, distribution, and abundance of plants at each station. In addition, type and quantity of substratum available for benthic plants were noted. The nomenclature of the Second Revised British Checklist (Parke and Dixon, 1968) was applied for most taxa of seaweeds, while the Eighth Edition of Gray's Manual (Fernald, 1950) was employed for the identification and nomenclature of vascular plants.

Species Composition of Intertidal Vascular Plants at Representative Habitats Along the Length of the Merrimack River Estuary:

Thirty-seven taxa of vascular plants were found in the marshy habitat of the Merrimack River Estuary (Table VII). All except *Spartina* spp. and *Scirpus* spp. (major components of the bank community along the shoreline), were found above mean high water. Fourteen of the 37

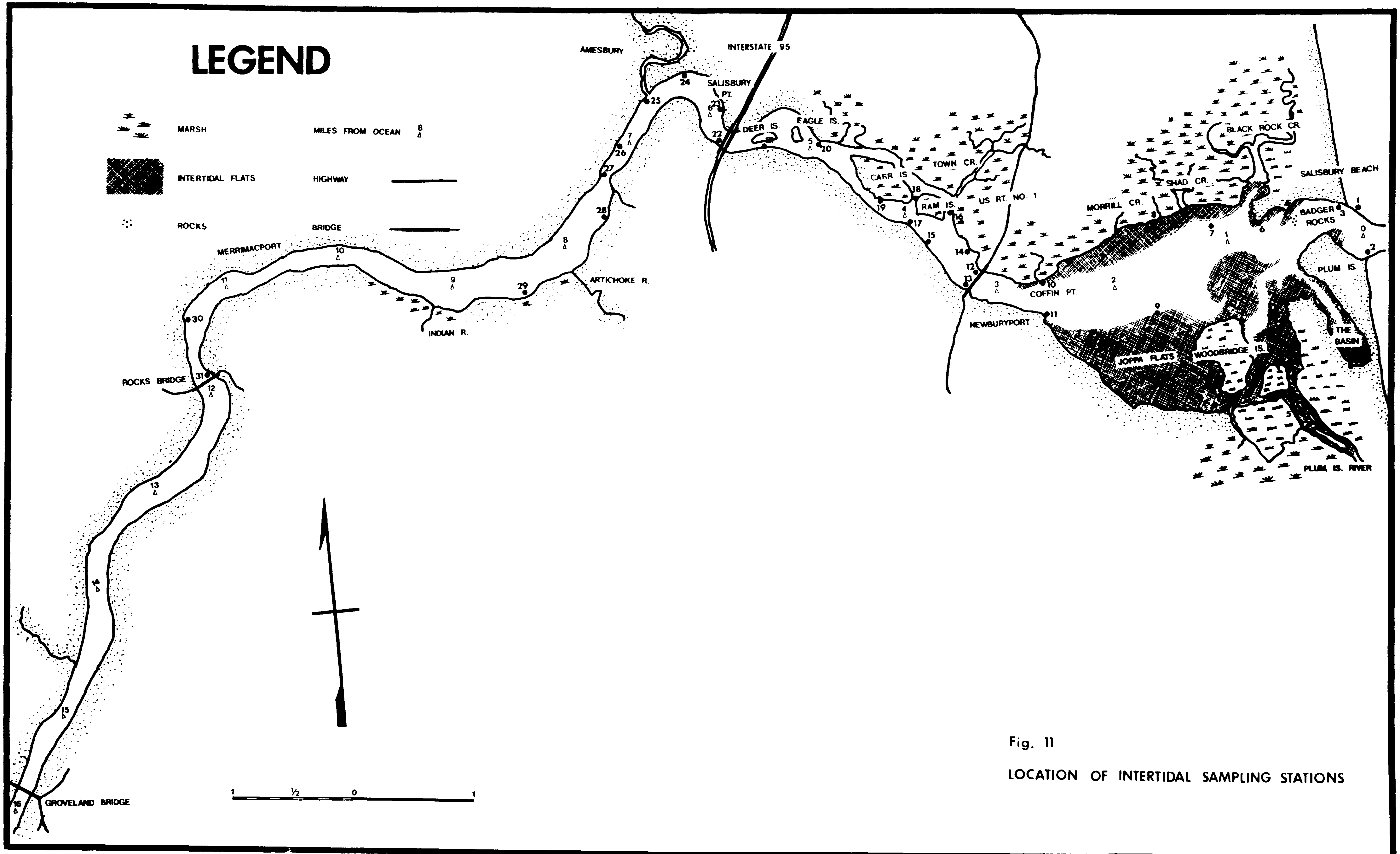


Fig. 11

LOCATION OF INTERTIDAL SAMPLING STATIONS

TABLE VII

VASCULAR PLANTS OF THE MERRIMACK RIVER ESTUARY

AND THEIR ESTUARINE DISTRIBUTION

Acnida cannabina L. Found in salt marshes and tidal shores.

Acorus calamus L. (Sweet flat or Flagroot) (older name for a reed) has an aromatic rhizome. Found in wet places and borders of quiet water. (Primarily found in freshwater.)

Ambrosia artemisiifolia L. (Ragweed). Ubiquitous distribution.

Ammophila breviligulata Fern. (Beach grass). Found on dunes and in sandy habitats near the open coast.

Artemisia stelleriana Bess. (Dusty Miller). Found on sandy beaches and dunes.

Aster subulatus Michx. A plant of saline marshes.

Atriplex patula L. var. hastata (L.) Gray (Orach). Found in saline, brackish or rich soils both on the coast and inland.

Bulbostylis capillaris (L.) C. B. Clarke. A plant of dry open soil.

Cakile edentula (Biegl.) Hook. (Sea-rocket). Found on sandy gravelly beaches and seacoast.

Carex salina Wahlenb. A true halophyte found on saline or brackish shores.

Cyperus filiculmis Vahl var. macilentis Fern. (Limited distribution)

Distichlis spicata (L.) Greene. (Spike grass). Grows in saline marshes.

Eleocharis acicularis (L.) R. & S. Commonly found on damp shores and low grounds.

Gnaphalium obtusifolium L. (Cat foot). Typically found in dry woods, clearings and on the edges of woods.

Hudsonia tomentosa Nutt. (Beach heath, poverty grass). Found on sandy areas primarily near the coast.

TABLE VII (continued)

Hypericum gentianoides (L.) BSP. (Orange grass). Found in sandy, sun baked soil.

Juncus gerardi Loisel. (Black grass). Saline areas and salt marshes.

Lathyrus japonicus Willd. (Beach Pea). Found on sandy beaches and dunes.

Limonium carolinianum (Walt.) Britt. (Sea-Lavender) L. or Nashii Small. Found in salt marshes almost exclusively.

Lythrum salicaria L. (Purple loosestrife). A plant of wet areas and river floodplains. This is considered a local nuisance in many New England areas. Often outcompetes other local species at times to their exclusion.

Plantago juncoides Lam. (Seaside Plantain). Mostly a maritime (shore side) species.

Plantago oliganthos R. & S. (Seaside Plantago). Grows in salt marshes and saline or brackish shores.

Polygonella articulata (L.) Meisn. Found in dry sandy habitats.

Polygonum hydropiper L. Common Smartweed. Grows in damp soils.

Potentilla egedei Warmsk. var. groenlandica (Tratt.) Polunin. Normally grows by the seacoast.

Salicornia europaea L. (Glasswort or Samphire). Grows primarily in salt marshes occasionally found inland.

Scirpus maritimus L. var. fernaldi (Bickn.) Beetle (Bullrush). Occurs from saline to brackish marshes and extending from brackish to freshwater (tidal) areas.

Scirpus validus Vahl. Found in brackish or fresh shallow water and marshes.

Sium suave Walt. (Water Parsnip). A plant of meadows, wet thickets and muddy river banks. (Primarily freshwater.)

Solidago sempervirens L. (Seaside Goldenrod). Found in saline, brackish or even freshwater habitats near the coast.

Spartina alterniflora Loisel. (Salt water cord grass). Grows on saline shores and marshes.

TABLE VII (continued)

Spartina patens (Ait.) Muhl. (Salt meadow grass). Grows on saline marshes and brackish shores.

Spergularia marina (L.) Griseb. Found in saline or brackish soils.

Triglochin maritima L. (Arrow-grass). Saline, brackish or fresh marshes and shores.

Typha latifolia L. (Cat-tail). Found in marshes as well as in shallow waters.

Zizania aquatica L. (Wild rice). River mouths growing in fresh to brackish waters. (Found in freshwater lakes and ponds.)

vascular plants collected were widely distributed, the others were sporadic in occurrence or only collected once. A detailed description of species composition at each station is presented in Table VIII and summarized in Figure 12.

No flowering plants were found in the intertidal zone at Stations 1 through 3. However, a fairly uniform distribution of typical salt-marsh plants was apparent from Station 5 to Station 19, with Spartina spp. dominating the bank community. Species consistently present included Solidago sempervirens, Spartina alterniflora, Spartina patens, Salicornea europea, Atriplex patula and Limonium sp. Several other species occurred sporadically within the bounds of Station 5 to Station 19 (e.g., Acnida cannabina, Potentilla egedei, and Juncus geradi). Scirpus validus was collected for the first time along the river at Station 14, but not again until Stations 26 through 29. Its limited abundance at Station 14 suggests that it was probably carried downriver intact by spring floods. Scirpus maritimus var. fernaldi was collected for the first time at Station 18, and with the exception of Station 20, persisted in noticeable abundance up to Station 29.

Station 20 was characterized by a diminished salt-marsh flora. Grazing activity (cows) may have contributed to this paucity of species. Only four species (Spartina alterniflora, Spartina patens, Atriplex patula, and Potentilla egedei) were found at this station. This was

TABLE VIII

SPECIES COMPOSITION AND DISTRIBUTION OF CONSPICUOUS VASCULAR PLANTS OCCURRING IN THE TIDAL REACHES OF THE MERRIMACK RIVER ESTUARY.

	STATIONS												
PLANT	4	5	6	10	11	14	18	19	20	23	27	28	29
Triglochin maritima						X							
Artemesia stelleriana	X	X											
Lathyrus japonicus	X	X											
Ammophila breviligulata	X												
Solidago sempervirens	X	X	X	X	X	X	X	X		X	X		
Spartina alterniflora		X	X	X	X	X	X	X	X	X	X		
Spartina patens		X	X	X	X	X	X	X	X	X	X		
Salicornia europea		X	X	X		X		X					
Ambrosia artemisiifolia		X	X		X		X						
Plantago juncoides		X	X										
Atriplex patula var. _hastata_		X		X	X	X	X	X	X				
Limonium carolineanum		X				X	X	X					
Lythrum salicaria			X				X						
Bulbostylis capillaris			X										
Cakile edentula			X										
Aster sp.			X										
Plantago oliganthos			X										
Cyperus filiculmis var. _macilentis_			X										
Hypericum gentianoides			X										
Polygonella articulata			X										
Carex salina			X										
Hudsonia tomentosa			X										
Gnaphalium obtusifolium			X										
Acnida cannabina				X	X	X	X			X	X		
Potentilla egedei var. _groenlandica_				X			X	X	X				

(continued)

TABLE VIII (continued)

PLANT	STATIONS 4	5	6	10	11	14	18	19	20	23	27	28	29
Juncus geradi				X			X						
Spergularia marina				X									
Eleocharis acicularis				X									
Rannunculus sp.				X							X		
Scirpus validus						X				X	X	X	X
Scirpus maritimus var. *fernaldi*							X	X		X	X	X	X
Typha latifolia										X	X		
Sium suave											X		
Acorus calamus												X	X
Zizanis aquatica												X	X
Polygonum hydropiper												X	
Aster subulatus												X	
Distichlis spicata							X						

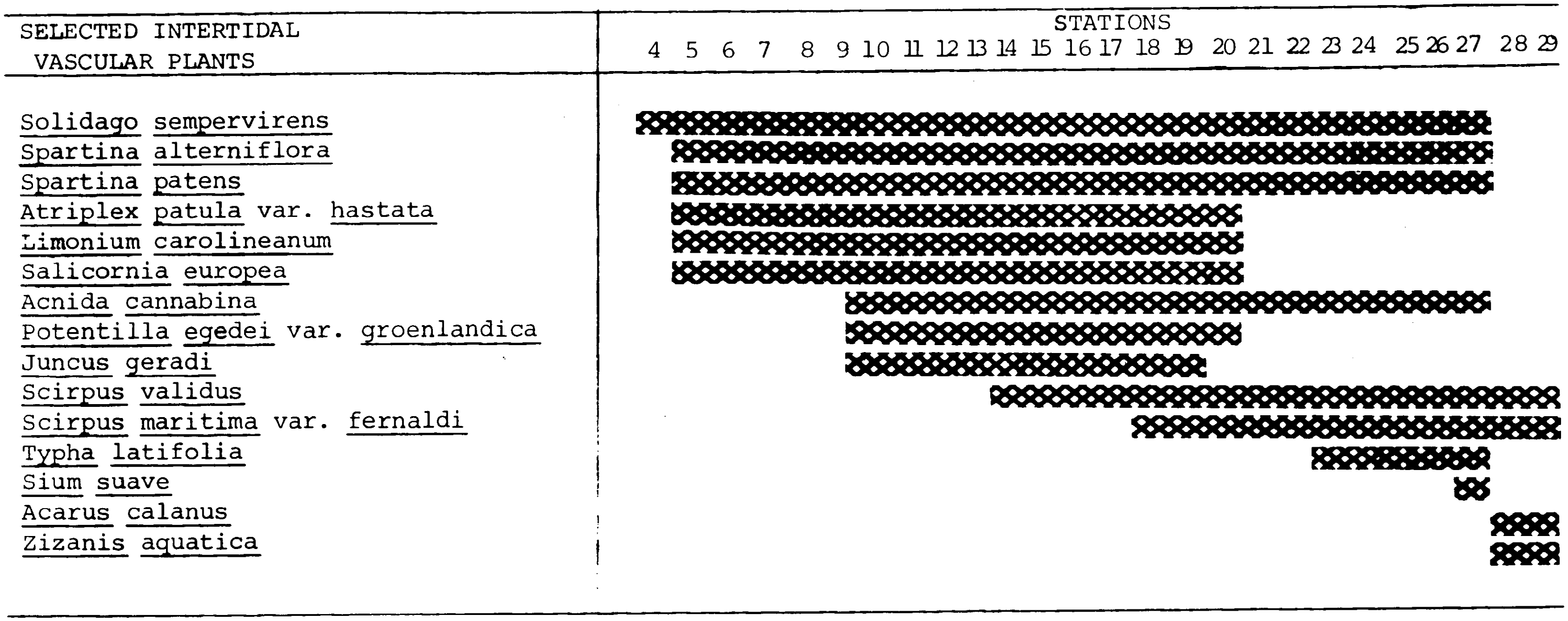


Figure 12. The distribution of selected intertidal vascular plants occurring along the Merrimack River Estuary, Massachusetts, 1971.

the last upriver station that Atriplex patula and Potentilla egedei were recorded. Scirpus maritimus var. fernaldi and Scirpus validus were again found at Station 23 and showed an increase in abundance over earlier stations. Typha latifolia, a species which occupies a niche in freshwater habitats similar to Spartina spp., was seen at Station 23 for the first time. Spartina alterniflora, Spartina patens and Acnida cannabina were still present.

Station 27 was the last station (upriver) at which Solidago sempervirens, Spartina alterniflora, Spartina patens, and Acnida cannabina were collected. Sium sauve was collected for the first time at this station in association with Typha latifolia and Scirpus validus. New associations were present at Stations 27 and 28 in the form of Scirpus validus, Scirpus maritimus, Acorus calamus, and Zizania aquatica. These four species are essentially brackish to freshwater inhabitants and represent a marked change in association away from some of the more persistent halophytes such as Spartina alterniflora, Spartina patens, Salicornea europea, and Solidago sempervirens. Both Spartina species, Salicornea sp. and Solidago sp. dropped off completely by Stations 28 and 29, probably due to a reduction in salinity.

Species Composition of Intertidal Algae at Representative Habitats Along the Length of the Merrimack River Estuary:

A total of 31 taxa of seaweeds was collected (Table IX).

TABLE IX

LIST OF THE ALGAL SPECIES OF THE MERRIMACK RIVER ESTUARY, THEIR LONGEVITY AND DISTRIBUTION

SPECIES	LONGEVITY	DISTRIBUTION
CHLOROPHYCEAE:		
Blidingia minima (Nägeli ex Kützing) Kylin	Annual	Cosmopolitan
Enteromorpha erecta (Lyngbye) J. Agardh	Annual	Cosmopolitan
Enteromorpha groenlandica (J. Agardh) Setchell et Gardner	Annual	Estuarine
Enteromorpha intestinalis (L.) Link	Annual ?	Cosmopolitan
Enteromorpha linza (L.) J. Agardh	Annual	Cosmopolitan
Monostroma oxyspermum (Kützing) Doty	Annual	Estuarine
Pseudendoclonium marinum (Reinke) Aleem et Schulz	Perennial	Cosmopolitan
Rhizoclonium riparium (Roth) Harvey	Annual	Cosmopolitan
Spongomorpha arcta (Dillwyn) Kützing	Annual	Coastal*
Ulothrix flacca (Dillwyn) Thuret in Le Jolis	Annual	Cosmopolitan*
Ulva lactuca (L.)	Annual ?	Cosmopolitan
Urospora penicilliformis (Roth) Areschoug	Annual	Cosmopolitan*
PHAEOPHYCEAE:		
Ascophyllum nodosum (L.) Le Jolis	Perennial	Cosmopolitan
Ectocarpus confervoides (Roth) Le Jolis	Annual	Cosmopolitan
Elachista fucicola (Velley) Areschoug	Perennial	Cosmopolitan*
Fucus vesiculosus (L.)	Perennial	Cosmopolitan
Fucus vesiculosus var. spiralis Farlow	Perennial	Estuarine
Laminaria digitata (Hudson) Lamouroux	Perennial	Cosmopolitan*
Laminaria saccharina (L.) Lamouroux	Perennial	Cosmopolitan*
Petalonia fascia (O. F. Müller) Kuntze	Annual	Cosmopolitan
Pilavella littoralis (L.) Kjellman	Perennial ?	Cosmopolitan
Ralfsia verrucosa (Areschoug) J. Agardh	Perennial	Cosmopolitan
Scytosiphon lomentaria (Lyngbye) Link	Annual	Cosmopolitan

*Documented by collections from other Massachusetts locations.

TABLE IX (continued)

SPECIES	LONGEVITY	DISTRIBUTION
RHODOPHYCEAE:		
Hildenbrandia prototypus Nardo	Perennial	Cosmopolitan
Polysiphonia fibrillosa (Dillwyn) Sprengel	Annual ?	Estuarine ?
Porphyra leucosticta Thuret	Annual	Coastal
Porphyra umbilicalis (L.) J. Agardh	Annual	Cosmopolitan
Ptilota serrata Kützing	Perennial	Coastal
XANTHOPHYCEAE:		
Vaucheria sp.	Perennial ?	Estuarine
BACILLARIOPHYCEAE:		
Amphipleura rutilans	Annual	Cosmopolitan
Melosira sp.	Annual	Cosmopolitan ?

Twelve Chlorophyceae (green algae), eleven Phaeophyceae (brown algae), and five Rhodophyceae (red algae) were identified. A detailed evaluation of the Cyanophyceae (blue-green algae), Xanthophyceae (yellow-green algae), and Bacillariophyceae (diatoms) was beyond the scope of the present investigation, although some data were collected. For example, the colonial diatom, Amphipleura rutilans, was a conspicuous component at Stations 1, 6, 8, and 14, and Vaucheria sp. and various blue-green algae (primarily species of Lyngbya, Oscillatoria and Merismopedia) formed a conspicuous mat amongst Spartina roots at many stations.

Details of species composition and distribution of seaweeds are summarized in Table X. The maximum number of species was found at Stations 1, 3, and 6, and beyond Station 6 there was a rapid and progressive reduction in species numbers. Red algae appeared to be least tolerant of reduced salinities. Three of the five species dropped out at Station 3, and no red algae were found beyond Station 10. Brown algae showed a wider distribution than red algae, but even so they were not found upstream of Station 14, and their largest number of species was found at Station 3. Green algae were the most cosmopolitan of the three major groups, with Enteromorpha erecta extending to the low salinities of Station 26. The yellow-green alga, Vaucheria sp., and the green alga, E. erecta, were the most widespread of all seaweeds. Blue-green algae are probably equally tolerant to reduced

TABLE X

SPECIES COMPOSITION AND DISTRIBUTION OF CONSPICUOUS INTERTIDAL ALGAE IN THE MERRIMACK RIVER ESTUARY

	STATIONS												
SPECIES	1	3	6	8	10	14	15	18	20	26	28	29	31
CHLOROPHYCEAE:													
Blidingia minima	X	X	X		X	X							
Enteromorpha erecta	X	X	X	X	X	X	X	X	X	X			
Enteromorpha groenlandica					X								
Enteromorpha intestinalis	X	X	X		X	X	X						
Enteromorpha linza	X	X	X	X									
Monostroma oxyspermum					X	X	X						
Pseudendoclonium marinum	X	X	X										
Rhizoclonium riparium							X						
Spongomorpha arcta	X												
Ulothrix flacca	X		X	X									
Ulva lactuca	X		X										
Urospora penicilliformis		X											
SUBTOTAL	8	6	7	3	5	4	4	1	1	1			
PHAEOPHYCEAE:													
Ascophyllum nodosum	X	X	X	X	X								
Ectocarpus confervoides	X												
Elachista fucicola	X												
Fucus vesiculosus	X	X											
Fucus vesiculosus var. *spiralis*			X	X	X	X							
Laminaria digitata	X												
Laminaria saccharina	X												
Petalonia fascia	X												

(continued)

TABLE X (continued)

SPECIES	1	3	6	8	10	14	15	18	20	26	28	29	31
						STATIONS							
PHAEOPHYCEAE (continued)													
Pilavella littoralis	X		X	X									
Ralfsia verrucosa	X	X											
Scytosiphon lomentaria	X												
SUBTOTAL	10	3	3	3	2	1							
RHODOPHYCEAE:													
Hildenbrandia prototypus	X	X	X		X								
Polysiphonia fibrillosa			X										
Porphyra leucosticta	X												
Porphyra umbilicalis	X												
Ptilota serrata	X												
SUBTOTAL	4	1	2		1								
XANTHOPHYCEAE:													
Vaucheria sp.			X	X		X	X	X	X	X	X		
SUBTOTAL			1	1		1	1	1	1	1	1		
CYANOPHYCEAE:													
Various blue-green algae			X	X		X	X	X	X	X	X		
SUBTOTAL			1	1		1	1	1	1	1	1		

(continued)

TABLE X (continued)

SPECIES	STATIONS 1	3	6	8	10	14	15	18	20	26	28	29	31
BACILLARIOPHYCEAE:													
Amphipleura rutilans		X	X	X		X							
Melosira sp.								X					
SUBTOTAL		1	1	1		1		1					
TOTAL	22	11	15	9	8	8	6	4	3	3	3	0	0

salinities, but lack of specific identifications precluded a precise evaluation.

An inspection of Table X indicates that most seaweeds (23) occurred both on the open coast and within the estuary, exhibiting a cosmopolitan distribution. Only five species (*Vaucheria* sp., *Enteromorpha groenlandica*, *Monostroma oxyspermum*, *Fucus vesiculosus* var. *spiralis*, and *Polysiphonia fibrillosa*) are considered to be truly estuarine, and were found exclusively within the estuary. Three species (*Spongomorpha arcta*, *Porphyra leucosticta*, and *Ptilota serrata*) appear to be coastal forms, since they were not found within the mouth of the river.

Factors Influencing the Distribution and Abundance of Plants in the Merrimack River Estuary:

The variety and abundance of rock are major factors restricting growth and distribution of algae in the Merrimack River Estuary. The breakwater at Stations 1 and 3 provided maximum stability and surface area for the growth of seaweeds, and highest species diversity and biomass of algae were found at these two sites. The reduced biomass and species diversity upstream of Station 3 can be attributed, at least in part, to unsuitable substratum. Most rocks upriver of this station were mud covered, and it is obvious that films of mud and silt will inhibit the attachment and growth of many algal species. In addition, small cobbles and pebbles, characteristic of upriver stations, are unsuitable as substrata for many larger plants because of their instability. Only crustose algae (e.g., *Hildenbrandia prototypus* and *Pseudendoclonium marinum*) were found on such rocks. *Vaucheria* sp., *Enteromorpha* spp., and various blue-green algae were the only forms collected on the muddy surfaces stabilized by the roots of *Spartina alterniflora* and *Spartina patens*. The *Spartina* spp. appear to play an important role in the formation of substrata suitable for algal colonization by such species.

In contrast, the rocky substratum at Stations 1 and 3 was not suitable for attachment and colonization of estuarine vascular plants, and progressive increases in species diversity of estuarine vascular plants was observed in relation to a decrease in the amount of rocky substratum upstream. Therefore, an increase in biomass and species diversity of vascular plants upriver can be attributed to suitable substratum, including small rocks and fibrous peat. Maximum species diversity occurred at Stations 18, 19, and 20. Beyond this point the reduction in species number (but not biomass) probably resulted more from sub-optimal hydrographic factors than from suitability of substrata. At these stations four vascular plants (*Scirpus* validus, Scirpus maritimus, Acorus calamus, and Zizania aquatica) accounted for nearly all the plant biomass.

Spatial and temporal variations of hydrographic factors in the Merrimack River Estuary, particularly the low upstream salinities, restrict the longitudinal distribution of many species. Species having limited tolerances to temperature and salinity changes would not be expected to migrate upstream for any distance. As suggested earlier, Spongomorpha arcta, Porphyra leucosticta, and Ptilota serrata have a distinctly coastal distribution, and they did not extend inland of Station 1. Other species exhibited gradations of tolerances to temperature and salinity fluctuations within the estuary. The most tolerant ones exhibited the widest distributions (e.g., Enteromorpha erecta and Vaucheria sp.) while the less tolerant ones had limited estuarine distributions (e.g., Elachista fucicola and Petalonia fascia). The most conspicuous reduction in species diversity occurred between Stations 6 and 8, probably caused by the greater fluctuations of temperature and salinity and the limited amount of solid substrata.

Pollution is often an important limiting factor in algal distribution and abundance. A comparison of species composition of seaweeds from the Merrimack River Estuary with that of the Hampton-Seabrook Estuary (Mathieson and Fralick, In Press) and the Great Bay Estuary Systems (Mathieson, Reynolds, and Hehre, In Press) of New Hampshire indicates a paucity of species in the Merrimack. A total of 118 taxa of seaweeds was collected from the Hampton-Seabrook Estuary and adjacent open coast, while over 150 species were found within the vicinity of the Great Bay Estuary System. The low species diversity (only 28 taxa) from the Merrimack River Estuary is in part due to the extreme domestic and industrial pollution of this interstate river. The concept of species diversity has been applied extensively in evaluating eutrophication of freshwater habitats. In general, a decrease in species diversity is a typical response to an increase in either domestic and/or industrial pollution. Under polluted conditions, a few tolerant species tend to dominate in large numbers and high biomass. The abundance of many Ulotrichalean green algae (e.g., *Enteromorpha* spp., *Ulva lactuca*, and *Monostroma* sp.) typifies a polluted estuarine habitat. The latter species are not only tolerant of extremes in pollution, but to gross fluctuations in hydrographic factors.

Possible Effects of Freshwater Diversion on Plants of the Merrimack River Estuary:

Little information is available concerning the optimal growth requirements of both seaweeds and higher plants, but it is generally assumed that juvenile stages are more sensitive to environmental changes than adult stages. Salinity is known to affect both growth and reproduction of marine plants, and it has been shown in certain species (i.e, *Porphyra* sp.) that germlings require low salinities (15 to 20 $^{o}/oo$) while adult plants grow best in higher salinities.

Low salinities can increase the respiration rate of plants and subsequently reduce their net photosynthesis (i.e., growth) and their reproductive success.

The net effects of higher salinities are not as well documented, but most studies indicate a broad tolerance to them, at least within the range expected to occur from a freshwater diversion. It would seem that the effects of increased salinities would be minimal on marine plants during both reproduction and growth of juvenile stages, but it is difficult to evaluate the effects of increased salinities on cosmopolitan species such as *Porphyra*, which reproduce best under low salinities. In addition, estuarine species that actually require a fluctuating temperature and salinity regime may not be able to reproduce effectively if this fluctuation is reduced.

As suggested previously, marine and estuarine plants vary in their tolerance to reduced salinities. Hence, those species which are euryhaline are the most widespread in an estuary, while stenohaline species are limited in distribution. One of the most obvious results of a freshwater diversion from the Merrimack River could be an alteration of the delicate balance between freshwater, brackish water, and marine organisms, evidenced by changes in distribution and abundance of species. An increase in salinity would no doubt allow the upstream movement of marine or estuarine algae such as *Ascophyllum nodosum* and *Fucus vesiculosus*, and subsequently alter the composition and dominance of algal species in a locale. Typically estuarine vascular plants such as *Spartina alterniflora*, *Spartina patens*, *Salicornea europea*, and *Solidago sempervirens* would also extend their distribution further upriver, probably at the expense of freshwater species such as *Scirpus validus*, *Scirpus maritimus* var. *fernaldi*, *Acorus calamus*, and *Zizania aquatica*.

It would seem that the true estuarine species would be the most vulnerable to increased salinities. Preliminary studies (unpublished data, A. C. Mathieson) suggest that several species, among them *Monostroma oxyspermum*, *Polysiphonia fibrillosa*, and *Polysiphonia elongata*, actually require low salinities. Comparable data is known for some shellfish (e.g., oysters), where mass mortalities have been recorded in association with alterations of salinities.

Secondary effects of such shifts in species distribution are difficult to predict. It is possible that alterations of photosynthetic productivity or disappearance of specific hosts for epiphytes and epizooans may result. As an example, the survival ability of several fish and invertebrates may be altered by a change in the *Typha latifolia* populations of brackish water locations. An increase in salinities might kill off this species, and limitations of other parameters such as pollution may not allow its re-growth upriver. Hence, the associated fauna could be eliminated because of loss of the primary host.

It is conceivable that other changes in plant communities may be initiated by associated effects of freshwater diversion such as alterations of current flow and velocity, changes in sediment transport and patterns of deposition, reduction of seasonal temperature variation, and changes in pollution load. Alterations of current flow (velocity) would no doubt be associated with differential transport of sediments, and a reduction of silt and mud deposition upriver may provide a greater availability of solid substrata for algal attachment. In addition, a reduction of turbidity would extend the depth of the photosynthetic zone, and contribute to a greater diversity and biomass of plants throughout the estuary. Plant communities could also be affected by changes in distribution of sand throughout the estuary. At present, sand is not evident beyond Station 4, and it is possible that with reduced flow more sand may be moved upriver. Differential communities of plants and animals are found in sandy versus muddy habitats, and some plants, specifically Ahnfeltia plicata (a psamophytic species), thrive in sandy habitats. Plants such as these might be introduced if a major alteration of substratum occurred. This, however, is not likely.

Changes in temperature may also affect plant communities. The water temperatures of the Merrimack River Estuary result, at least in part, from the mixing of freshwater and salt water. Differential temperatures of the two bodies often result in intermediate temperatures, as well as cold and warm extremes, and these pronounced seasonal variations of temperature in the Merrimack River Estuary are correlated with major fluctuations in plant populations. Thus, the flora is heterogeneous and it is composed of both cold (boreal) and warm (temperate) water components. Any major alteration of temperature could change the composition of the vegetation, particularly the annual **components**.

4. Intertidal Invertebrates:

Methods:

Collections and observations of conspicuous intertidal invertebrates were made at selected sites (Figure 11) throughout the Merrimack River Estuary during high and low flow periods of 1971. To develop a broad overview of the intertidal zone from open ocean to freshwater, 29 stations were sampled during the spring (Stations 1 through 26, and Stations 30 and 31). This number was reduced to 12 representative stations during the fall (Stations 1, 3-6, 10, 14, 18-20, 23, and 27). Emphasis was placed on the invertebrates of rocky habitats, although organisms from other types of substrata adjacent to the rocks were also studied. Where positive field identification was not possible, the organisms were collected, preserved, and returned to the laboratory.

Species Composition of Intertidal Invertebrates at Representative Habitats Along the Length of the Merrimack River Estuary:

Forty-seven species of invertebrates representing six phyla were collected in the Merrimack River Estuary during the sampling period (Table XI.). Sixteen of these species were found only outside the estuary where physico-chemical conditions approximate the oceanic environment. Twenty-six species were found within the estuary where extreme hydrographic fluctuations occur. Five species were restricted

TABLE XI. SPECIES COMPOSITION AND DISTRIBUTION OF CONSPICUOUS INTERTIDAL INVERTEBRATES IN THE MERRIMACK RIVER ESTUARY - 1971.

SPECIES \ STATION NUMBER	1	2*	3	4	5	6	7*	8	9*	10	11*	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
SERTULARIA PUMILA	X																														
CORDYLOPHORA LACUSTRIS																			X		X		X								
NEREIS VIRENS (clam worm)				X	X	X																									
HARMOTHOE IMBRICATA (scale worm)	X																														
LEPIDONOTUS SQUAMATUS (scale worm)	X																														
SCOLELEPSIS SQUAMATA						X																									
NEREIS DIVERSICOLOR								X		X		X	X	X	X	X		X	X	X	X	X									
OLIGOCHAETES						X				X						X	X		X	X	X	X	X	X	X	X					
LEECH # 1																														X	X
LEECH # 2																														X	X
LEECH # 3																														X	X
LEECH # 4																		X													
LEPIDOCHITON RUBER (a chiton)	X																														
ACMAEA TESTUDINALIS (limpet)	X																														
LACUNA VINCTA (Atlantic chink shell)	X																														
POLINICES HEROS (moon snail)	X			X																											
THAIS LAPILLUS (dog whelk)	X		X	X																											
LITTORINA LITTOREA (common periwinkle)	X	X	X	X	X	X		X		X																					
LITTORINA SAXATILIS (rough periwinkle)	X	X	X	X	X	X																									
DENDRONOTUS FRONDOSUS	X																														
ONCHIDORUS FUSCA	X																														
MESODESMA ARCTATA	X																														
MODIOLUS DEMISSUS (horse mussel)					X																										
MYTILUS EDULIS (common blue mussel)	X	X	X	X	X	X	X	X	X	X																					
MYA ARENARIA (soft-shell clam)						X		X	X																						
MACOMA BALTHICA (little macoma)						X																									
FERRISSIA SP.																															X
HELISOMA SP.																														X	X
PHYSA SP.																X		X	X	X	X	X	X		X	X				X	X
BALANUS BALANOIDES (common barnacle)	X		X	X	X	X	X	X		X				X				X	X												
BALANUS IMPROVISUS	X		X	X	X	X	X			X																					
IDOTEA BALTICA	X																														
CANCER COREALIS (Jonah or Northern crab)				X																											
GAMMARUS OCEANICUS	X		X	X	X	X				X				X																	
HAUSTORIUS CANADENSIS						X				X																					
JAERA MARINA					X	X		X		X		X	X		X																
GAMMARELLUS HOMARI	X																														
JASSA FALCATA	X																														
CALLIOPIUS LAEVIUSCULUS	X																														
GAMMARUS TIGRINUS								X		X		X	X	X	X	X	X	X	X	X	X		X								
COROPHIUM VOLUTATOR																X		X	X												
CYATHURA POLITA																		X	X	X	X	X	X	X		X	X				
GAMMARUS FASCIATUS																					X	X	X	X	X	X	X			X	X
ELECTRA PILOSA	X																														
ASTERIAS VULGARIS (purple star fish)	X																														
STRONGYLOCENTROTUS DROEHBACHIENSIS (sea urchin)	X																														
TOTAL NUMBER OF SPECIES	24	3	7	10	9	13	3	7	2	10	0	3	3	4	3	5	2	7	8	5	7	5	6	3	3	4	2	0	0	6	7

S = SPRING F = FALL ░ = RANGE OF DISTRIBUTION X = ACTUAL OCCURRENCE

*CURSORY SPOT CHECK ONLY

to the freshwater habitat. Of the 26 species living within the estuary, 19 are euryhaline marine organisms found also in marine environments, four are true estuarine organisms found exclusively in the estuarine environment, and three are freshwater species capable of withstanding periodic low level salinities.

The maximum number of species was found at Station 1, a typical open ocean rocky habitat (Figure 11), where 24 species were collected throughout the study period. Sixteen of those species were stenohaline marine forms such as _Strongylocentrotus droehbachiensis_ and _Asterias vulgaris_, while the remaining ones were euryhaline marine organisms. This habitat was dominated by extremely abundant sets of _Mytilus edulis_ and _Balanus_ spp., and large numbers of their predators, _Thais lapillus_. _Littorina littorea_ was extremely abundant in the mid-tidal zone, as was _L. saxatilis_ in the upper intertidal. Large numbers of small _Asterias vulgaris_, _Dendronotus frondosus_, and several species of gammarids predominated in the tide pools, and extremely abundant populations of _Mesodesma arctata_ lived in the sand surrounding the rocks.

Even though marine conditions predominate at Station 3 through 6 during much of the year, no stenohaline marine species were found at these locations. This is probably due to the lethal effects of periodic low salinities during flood periods. Seven to 13 euryhaline marine species were found on the rocky substratum. Extensive beds of _Mytilus edulis_, moderate sets of _Balanus_ spp., and large numbers of *Gammarus oceanicus* living under the rocks predominanted. *Thais lapillus*, a species which preys upon *Mytilus* and *Balanus*, was scarce at Stations 2 and 3, and did not extend beyond Station 4.

Euryhaline marine organisms continued to predominate from Stations 7 through 10, but showed a steady decline in both species numbers and abundance with upriver progression. *Balanus* spp. and *Mytilus edulis* were extremely abundant at Stations 6 and 7, but *Balanus* spp. abundance dropped drastically beyond this point, and *M. edulis* was scarce at Station 10. *Littorina saxatillis* was not found beyond Station 8, and other euryhaline marine species such as *M. edulis* and *L. littorea* were last seen at Station 10.

The invertebrate community between Stations 12 and 17 differed from all previous locations in that species diversity was extremely low, estuarine organisms dominated, and the fauna was found not on the surface of the rocks, but rather under them. This community was characterized by large numbers of gammarids (primarily *G. tigrinus*) and oligochaetes living on the surface of the mud, and an abundance of *Nereis diversicolor* in mud tubes. Only five species of marine organisms extended beyond this point. One species, *Jaera marina*, was present during both spring and fall, while *Balanus* spp. spat and three species of amphipods were only found during the fall, having migrated into this region during the higher salinities of late summer.

Estuarine species continued to dominate the community beyond Station 17, but in association with an increasing number of salt tolerant freshwater species. As at previous stations, the community was composed of large numbers of *G. tigrinus*, oligochaetes, and *N. diversicolor*. *Balanus improvisus*, the only remaining marine species, was last found at Station 19. *Physa* sp., a freshwater snail, appeared for the first time at Station 10; the freshwater hydroid, *Cordylophora lacustris*, was first found at Station 19; and *G. fasciatus*, a salt tolerant freshwater amphipod, replaced the estuarine *G. tigrinus* beyond Station 21.

The intertidal invertebrate community beyond Station 21 can best be described as being an impoverished freshwater association. This probably results from a combination of high pollution and periodic low level salt intrusion. It was composed exclusively of high numbers of both oligochaetes and *G. fasciatus* living in the anoxic muck under rocks. *Nereis diversicolor* did not extend upriver of Station 22, and the last remaining estuarine species, *Cyathura polita*, was present in low abundance under rocks up to Station 29.

Beyond Station 30 species diversity increased significantly, and the community consisted of typically freshwater organisms.

The Relationship of Salinity to the Present Distribution of Intertidal Invertebrates in the Merrimack River Estuary:

A thorough examination of the distribution of intertidal invertebrates in the Merrimack River Estuary reveals a definite progression of invertebrate associations extending from the open ocean to the freshwater river. No definite boundaries exist which could serve to separate one association from the next, but for the purposes of discussion, these associations and their locations in the river can be roughly classified as follows (Figure 11):

Marine	Open ocean (Station 1)
Euryhaline marine	0-1 miles upriver (Stations 2-6)
Estuarine	1-5 miles upriver (Stations 7-21)
Impoverished freshwater	5-9 miles upriver (Stations 22-29)
Freshwater	Above 9 miles (Stations 30+)

The nature of these associations, and the manner in which salinity may determine their development at a particular location in the estuarine system are discussed below.

A study of the intertidal habitat in the Merrimack River Estuary provides an illustrative example of the effects of adverse environmental conditions on two broad groups of organisms, the marine invertebrates and the freshwater invertebrates. Organisms in both of these groups are generally best adapted for living in a relatively stable environment, and come under increasing physiological stress as physico-chemical conditions fluctuate from the optimum. Since the majority of marine and freshwater species are particularly intolerant of major fluctuations in salinity, highest species diversity in these two groups in an unpolluted estuarine system would be found in the open ocean and in the freshwater river, respectively, where the salinity is uniformly high or uniformly absent throughout the year.

The situation within an estuary is entirely different. Here physico-chemical conditions fluctuate significantly, and salinities cover the broad spectrum from salt to freshwater. Failure to osmoregulate and/or tolerate flucutations in body fluids is most important in restricting many intertidal invertebrates from this habitat, and thus the estuary proper in inhabited by associations of species that have varying degrees of tolerance to salinity fluctuations. Usually the number of true estuarine species, i.e., those found only in estuaries, is low. The remaining organisms in an estuarine community are either marine or freshwater species that have developed a limited ability to survive sub-optimal salinities.

The marine association found at Station 1 contained the highest number of species found at any location in the estuary, and approximately 75% of these species were stenohaline. Hydrographic conditions in this area are relatively constant, and all 24 species inhabiting this area are characteristic of the oceanic environment. However, the freshwater habitat at and above mile 11 (Station 30+) contained a relatively low number of invertebrates (seven), all of them typically freshwater species. While this number is higher than in the upriver stations subject to low level salt intrusion, it is well below expectations for an unpolluted river. Probably the combined pollution effects, including low oxygen and constant silting, have acted to eliminate all but the pollution tolerant species.

The euryhaline marine association found from the mouth of the estuary to approximately one mile upriver (Stations 2 through 6) is in reality an attenuated extension of the open ocean community found at Station 1. All organisms living in this region are generally found in the oceanic environment, but in contrast to the stenohaline forms found at that habitat, these organisms are capable of surviving under periodically reduced salinities. This environment, however, does not support any true estuarine species.

In the estuarine zone extending from mile 1 through approximately mile 5 (Stations 7 through 21), five species of true estuarine invertebrates are found in association with a variable number of euryhaline marine and salt-tolerant freshwater species. Progressing upriver, the euryhaline marine organisms rapidly drop out, and the associtation becomes dominated by the true estuarine species. Salinity fluctuations in this area are drastic, and may change from below 5 $^{o}/oo$ at ebb tide to well above 25 $^{o}/oo$ on the flood. Species diversity in this environment is usually lower during months of high river discharge, and increases as river flows drop in late summer and early fall. At this time motile euryhaline marine species, including spat of sessile forms, may migrate into the area, producing a noticeable increase in species numbers. For example, during the 1971 sampling, young *Mytilus*, *Balanus*, *Littorina*, and *Gammarus oceanicus* moved considerable distance upriver. In fact, *Balanus* sp. spat had successful sets nearly three miles beyond the limits of the spring distribution. It is likely, however, that these species will not be able to establish themselves permanently, but rather will be eliminated during the next flood period.

The estuarine fauna becomes progressively reduced from miles 5 through 9 (Stations 21 through 29), and increasing numbers of salt tolerant freshwater species begin to appear. Salinities are too low for most estuarine species, and periodically too high to permit establishment of freshwater species. In addition to the effects of salinity, most species in this habitat suffer from pollution induced oxygen deficiency and loss of suitable substratum due to silt and sludge deposition. Because of the severity of environmental conditions, this region presently contains the most unsuitable intertidal habitat in the Merrimack estuarine system.

Species diversity increases in the freshwater zone beyond mile 8 (Stations 30 and 31), but it is well below that found in other rivers of comparable size (Oldaker, 1966). This low species diversity is probably due to the effects of gross pollution, for the area is not affected by salinity intrusion.

Potential Effects of Freshwater Diversion on the Intertidal Invertebrates of the Merrimack River Estuary:

A complex interaction of physical, chemical, and biological factors operates to establish the existing pattern of invertebrate distribution, and it is probable that four changes resulting from diversion could significantly effect the ecology of the intertidal habitats of the Merrimack River Estuary. These are an increase in salinity, a fluctuation in pollution, a reduction in sedimentation, and shifts in intertidal floral distribution. These changes would probably result from a continuous diversion scheme, rather than from diversion only during periods of high flow. Each possible change can best be evaluated by discussing separately the effects, where applicable, on each invertebrate association found along the length of the estuary.

The stenohaline marine association at Station 1 should not be affected in any manner by freshwater diversion, since the habitat presently is under little influence from the estuarine environment. The area is exposed to open ocean salinities throughout most of the year, is little affected by the gross pollution from the Merrimack River, and already has a stable, well developed marine flora.

Some changes in species composition, however, may occur in the euryhaline marine zone extending from the end of the breakwater upriver to approximately mile 1. It is likely that with an increase in salinity there will be a net migration of several additional marine species into the area, and an increase in abundance of some marine species already there. Probably the most conspicuous of the migrants would be *Thais lapillus*, which is presently found in low abundance just inside the breakwater, but does not extend upriver of Station 4. If salinity increase results in an increase in abundance of *Mytilus* and *Balanus*, it is probable that *Thais* could become well established in the estuary. Other marine organisms may also move into this part of the estuary from outside the breakwater, but an introduction of these species should not lead to interspecific competition, since they presently exist outside the estuary.

More significant changes could occur in the estuarine zone extending from miles 1 to 5, but the net effect of these changes would undoubtedly be to increase the total number of species. There should be a net upriver migration of several species through the length of the estuary. In the lower estuary, this shift could bring euryhaline marine organisms into the area now occupied by estuarine species, and could result in possible interspecific competition. For example, *Nereis virens* is a clamworm living in euryhaline marine mud flats, and *Nereis diversicolor* occupies a similar niche in the estuarine zone. It is probable that with salinity increase *Nereis virens* could extend its distribution into the habitat now occupied by *Nereis diversicolor*, and physiological stress and competition for habitat could lead to the elimination of the latter species. Similarly, *Gammarus oceanicus*, a euryhaline marine amphipod, may migrate upriver into the area now inhabited by *G. tigrinus*, its estuarine counterpart, and one species may be eliminated through physiological stress or competition. The tendency of *G. oceanicus* to extend its range was evidenced between the spring and fall of 1971, when it migrated more than four miles upriver under the influence of late summer increased salinities. As will be discussed in a later section, it is also possible that clam predators such as the green crab, moon snail, and horseshoe crab could migrate onto the clam flats that are presently free from predators, leading to increased clam predation. In addition, if algal and vascular plant growth is enhanced either through increased salinities or decreased sedimentation as has been suggested in an earlier discussion, it is probable that intertidal invertebrates now feeding or living on these plants in the lower zones will move into this area to fill the newly established niche.

Changes may also occur in the upper estuary. Some salt tolerant freshwater species such as Physa sp. and Cordylophora lacustris, now present in low abundance in the upper reaches of the estuarine zone, may shift further upstream with increased salinity. It is also possible that Gammarus fasciatus, the freshwater amphipod that presently replaces Gammarus tigrinus above Station 21, may be displaced further upriver.

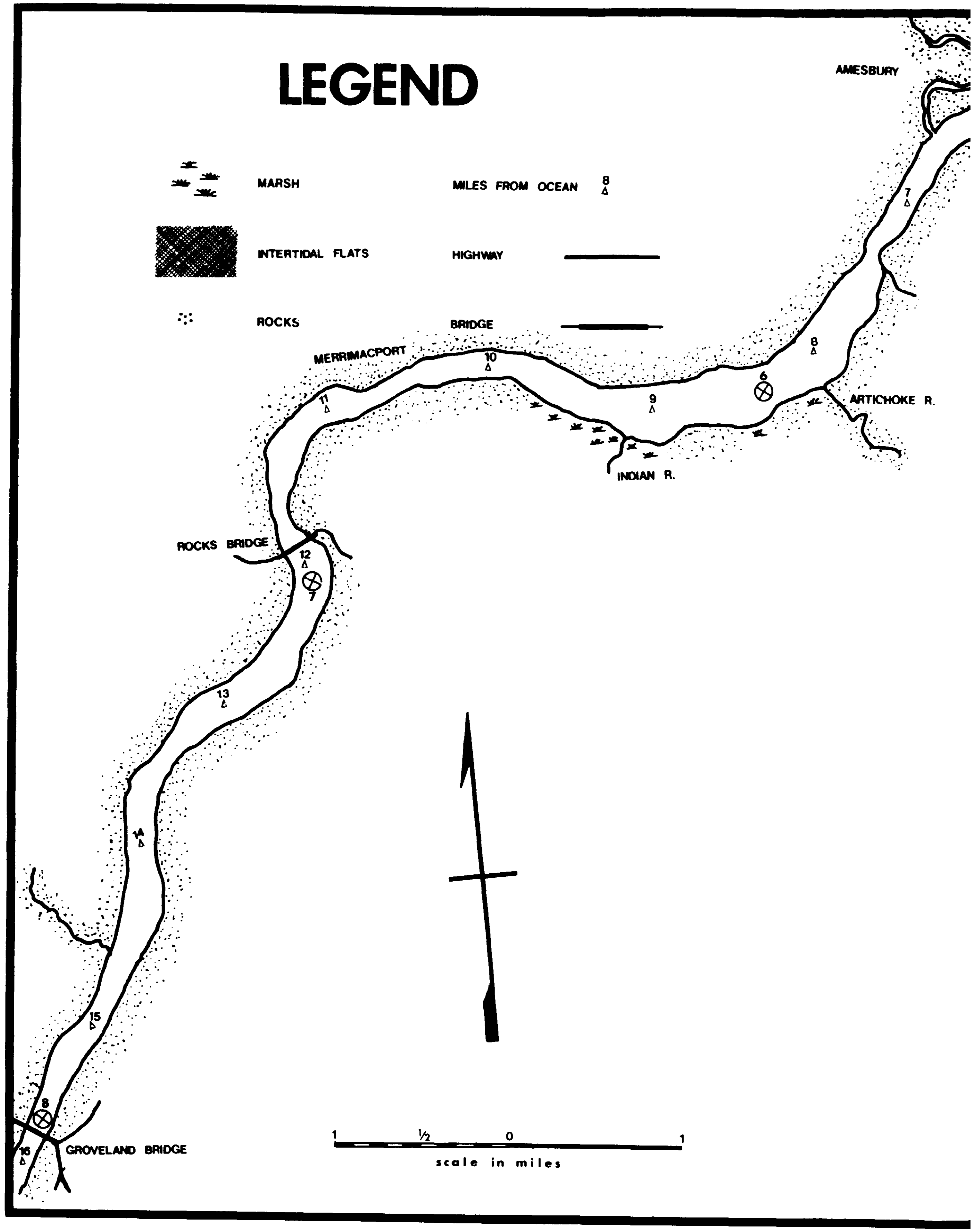
Any change in the impoverished freshwater zone extending from miles 5 to 9 will probably be beneficial. This zone is now in a serious state of ecological stress due to a combination of pollution and low level salt intrusion. A decrease in discharge would probably permit migration of some estuarine species into this area, but should have little effect on the few salt tolerant freshwater species existing there in low abundance, since they presently are found in higher salinities downriver. If diversion is preceded by a decrease in pollution, accompanied by an increase in oxygen and lowering of sedimentation, a further enrichment of the fauna in this habitat would result.

Since the salt water, after diversion, would not intrude beyond the limits presently reached, no migration of estuarine organisms into the freshwater zone is possible. However, a decline in pollution and lowering of sedimentation should increase the diversity of the freshwater fauna.

C. SUBTIDAL BENTHIC INVERTEBRATES

Free swimming invertebrates and most finfish are able to migrate when adverse environmental conditions arise. However, infaunal invertebrates (invertebrates living in or associated with bottom sediments) are restricted in movement and therefore must be able to withstand changing conditions in order to survive. In the open ocean the benthic environment is relatively free from drastic physical changes, and substantial numbers of infaunal species are found in this habitat. In an environment such as an estuary, where dramatic physical and chemical changes occur within each tidal cycle and throughout the year, the number of species able to survive is considerably less (Gunter, 1961). In view of these circumstances, many of these organisms are living at the limits of their physiological tolerance, and any additional stress, such as that associated with pollution, may eliminate all but the hardiest.

Benthic organisms can often be utilized as important indicators of ecological imbalance or stress. Therefore, subtidal benthic sampling was conducted to determine the species composition and distribution of this biological component of the Merrimack River Estuarine environment (Figure 13).



LEGEND
MARSH
INTERTIDAL FLATS
ROCKS
MILES FROM OCEAN
HIGHWAY
BRIDGE
AMESBURY
MERRIMACPORT
ARTICHOKE R.
INDIAN R.
ROCKS BRIDGE
GROVELAND BRIDGE
scale in miles

1. Methods

Using a Van Veen grab, three samples were taken during August, 1971 in midchannel at each of the eight locations along the length of the tidal estuary from Route 113 Bridge in Groveland to the open ocean beyond the Plum Island Breakwater (Table XII). The samples were placed in large plastic bags, labeled, and returned to the laboratory where they were sieved through a standard sieve series. The organisms retained by the sieves were preserved in 70% alcohol and later identified. Sediment samples were also collected at each station and readings of depth, temperature, and conductivity were recorded.

2. General Results

Sediments in the region of saltwater influence (Stations 1 through 6) were composed primarily of gravel, mixed with lesser amounts of pebbles and small stones, while sediments collected at the two freshwater stations (Stations 7 and 8) were much less homogeneous, ranging from pebbles and gravel to fine sand and silt (Table XIII) Hartwell (1970) found similar sediment composition in the estuary channel.

Eighteen species of bottom invertebrates were found during the sampling period, but only fifteen were collected alive. Of these fifteen species three were marine, three were true estuarine, and the

TABLE XII

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

BENTHIC STATION DESCRIPTIONS

STATION *	DESCRIPTION
1	In channel outside of Plum Island breakwater
2	In channel off Badger's Rocks
3	In channel off Morrill Creek
4	In channel off Coffin Point
5	In channel halfway between Eagle and Carr Islands
6	In channel halfway between entrances of Artichoke and Indian Rivers
7	In channel just upriver of Rocks Bridge, West Newbury
8	In channel just upriver of Groveland Bridge

*see map, Figure 13, page V-51.

TABLE XIII

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

PREDOMINANT BOTTOM SEDIMENT CHARACTERISTICS AT BENTHIC STATIONS

STATION *	DEPTH (In Feet)	CHARACTERISTIC BOTTOM TYPE
1	18'	Gravel
2	24'	Gravel
3	20'	Gravel
4	16'	Gravel & Pebbles
5	15'	Gravel & Pebbles
6	22'	Gravel & Pebbles
7	10'	Pebbles, Coarse Gravel Sand and Mud
8	11'	Rock through Mud

*see map, Figure 13, page V-51.

remainder were typically freshwater species. The largest number of species found at Stations 7 and 8, both freshwater stations. No living organisms were collected at three of the estuarine stations, and diversity was extremely low at the remaining stations (Table XIV).

3. Analyses According to Sampling Stations

STATION NO. 1: This site is located well beyond the mouth of the estuary, and is under influence of open ocean water for a considerable portion of the year. Salinities range upward from 30 ^{o}/oo and the habitat is subject to extreme turbulence at various portions of the tidal cycle, with sediment composed primarily of coarse gravel.

Only one species, the marine bivalve *Mesodesma arctata*, was collected. Abundance was extremely high, with as many as 130 specimens from several age classes found in one sample. Some indication of the severity of bottom conditions can be seen from the observations that this bivalve is usually found in abundance on surf beaches such as those of Salisbury Beach and Plum Island.

STATION NO. 2: Sediments are similar to those found at Station 1, but salinity variation is somewhat greater, especially during periods of high river flow.

Only two species were collected at this site. Large *Mesodesma*

TABLE XIV

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

Distribution and Abundance of Subtidal Benthic Animals

SPECIES	STATIONS 1	2	3	4	5	6	7	8	SALINITY RANGE
Annelida									
Oligochaetes							X	X	?
Nereis diversicolor				X					Estuarine
Leech #5								X	Freshwater
Mollusca									
Mytilus edulis		X							Marine
Mesodesma arctata	X	X							Marine
Pisidium sp.							X	X	Freshwater
Ligumia sp.								X	Freshwater
Sphaerium sp.							X	X	Freshwater
*Mya arenaria**			X						Marine
Physa sp.								X	Freshwater
Ferrissia sp.*									Freshwater
Gyraulus sp.*									Freshwater
Amnicola sp.								X	Freshwater
Helisoma sp.								X	Freshwater
Arthropoda									
Cyathura polita				X			X		Estuarine
Gammarus tigrinus				X			X		Estuarine
Gammarus fasciatus								X	Freshwater
Haustorius canadensis				X					Marine

*Collected dead.

were found in low abundance in two grabs, with no small individuals present. One individual of *Mytilus edulis* was also collected.

STATION NO. 3: No living macro-organisms were found in the coarse gravel at Station 3, although Oldaker (1966) found two species, *Mya arenaria* and *Nereis* sp., living in the fine sediments inshore from this location. Salinities in this area have a wide range from above 30 $^{o}/oo$ to below 5 $^{o}/oo$.

STATION NO. 4: Salinities at this station have a range similar to those observed at Station 3. Three estuarine species (the polychaete, *Nereis diversicolor*; the isopod, *Cyathura polita*; and the amphipod, *Gammarus tigrinus*) and one marine species (the amphipod, *Haustorius canadensis*) were collected. Oldaker (1966) reported two of these species, *Nereis* sp. and *G. tigrinus*, plus specimens of *Mytilus edulis*.

STATION NO. 5: No macro-organisms were collected from this station, although Oldaker (1966) reported two estuarine species, *Cyathura polita* and *Gammarus tigrinus*, in the vicinity. Both of these species are tolerant of the extreme fluctuations in salinity occurring in the area.

STATION NO. 6: Water in this area is fresh for a considerable portion of the year, but sufficient salt intrusion occurs during periods of low flow to restrict the establishment of freshwater organisms.

No living macro-organisms were found, and Oldaker (1966) reported only a few specimens of Cyathura polita in the vicinity.

STATION NO. 7: The habitat at Station 7 is characterized by sediment of various grades from mud to coarse gravel, and while predominately freshwater, is subject to low level salt intrusion during periods of reduced flow. At least five species of benthic organisms were found in this habitat. Two of them, Pisidium sp. and Sphaerium sp., are small, relatively pollution tolerant freshwater bivalves that are present at various points along the length of the freshwater river. Large numbers of very small oligochaetes were also found, but it has not been possible to identify them. In addition, two estuarine species, Cyathura polita and Gammarus tigrinus, were collected in low numbers in all grabs.

Oldaker (1966) found five species in bottom samples taken from this region. The estuarine species, Cyathura polita and Gammarus tigrinus, were present in moderate abundance, as were two species of freshwater midgeflies and a species of sludgeworm.

STATION NO. 8: The habitat at Station 8 has no characteristic bottom type, but ranges from rock to gravel and sand into silt and mud.

We have no record of saline water ever reaching this region of the river.

At least nine species of invertebrates were found, most being pollution tolerant freshwater species. The estuarine amphipod, *Gammarus tigrinus*, has dropped out and been replaced by *Gammarus fasciatus*, and the number of freshwater molluscan species has increased from two at Station 7 to six at Station 8. Three of these molluscs are bivalves, and three are gastropods. Only one species of leech was found at this station, although leeches were quite abundant at intertidal stations in the vicinity.

Oldaker (1966) found eight species of invertebrates in bottom samples taken from this region, all of them freshwater species with the exception of *Mya arenaria*, which is without question a mistaken identification. Of the seven valid species, one was the bivalve *Pisidium*, three were pollution tolerant midgeflies, two were leeches, and one a sludgeworm.

4. Discussion

It is obvious from the above descriptions that the benthic fauna of the Merrimack River Estuary is extremely limited. Oldaker (1966) came to similar conclusions, finding only eight species from 24 stations along the same length of river. This condition is probably brought about by a combination of five interrelated factors: 1) the prevalance of a mixed gravel/pebble substratum; 2) the occurrence of widely fluctuating and rapidly changing salinities throughout the estuary; 3) the high pollution load resulting from industrial and domestic sewage; 4) turbulence; and 5) scouring.

While large numbers of species of marine and estuarine epifaunal organisms are generally found in rocky habitats in the shallow subtidal zone (Oldaker, 1966), and smaller but still substantial numbers of infauna are found in submerged mud and sand flats, species diversity is generally low in habitats composed of mixed pebbles and gravel (Southward, 1965). The presence of pebbles and gravel indicates currents and waves sufficiently strong to disturb the substratum and remove all fine components. Conditions for survival are severe in regions where the sediment is subject to this frequent disruption, and few organisms are able to adapt to this environment.

Of the organisms that can survive a shifting substratum, many are restricted from the Merrimack River estuarine habitat by the widely fluctuating and rapidly changing salinity. Animals are able to maintain themselves in this type of environment either because they can regulate the concentration of their body fluids independently of the environment (i.e., they can osmoregulate), or because they can tolerate rather large changes in the concentrations of their body fluids. Most invertebrate species cannot do either, thus the fauna in areas of wide salinity variations is usually limited when compared with marine environments (Potts and Parry, 1963).

As important as the salinity changes in reducing species diversity is the effect of high pollution load, with resulting anaerobic conditions in the sediment and low oxygen tension in the overlying waters (Patrick, 1949). Few species can survive under such conditions. The relatively low diversity at Station 8, where salt intrusion does not occur and where a variety of substrata are found substantiates this.

Because a low benthic species diversity was found throughout the estuary resulting from a combination of factors, it is difficult to hypothesize on the effects of diversion. The existing maximum upriver intrusion of salt water will not change, so unless abatement of pollution produces more optimum conditions, an increase in species in the freshwater zone should not occur. However, the portion of the estuary now subject to salt intrusion will be saline more often, probably resulting in a net upriver migration of some estuarine and marine species, particularly those with larvae now existing as plankton in the Merrimack River Estuary. The extent of the upriver migration cannot be predicted at this time.

D. PLANKTON

Plankton studies are important for several reasons. Except for microbes, plankton are the most abundant group of organisms in the estuarine environment. In addition, they constitute the base of food chains upon which larger organisms depend, and any change in their distribution and/or abundance will affect higher trophic levels. Furthermore, a knowledge of the longitudinal distribution of meroplankton (organisms which are temporarily planktonic) under varying river discharges, correlated with some knowledge of the salinity tolerances of the adults, can be used to predict the potential upriver migration of intertidal and subtidal invertebrates after diversion.

The objectives of this study were to describe present plankton associations within the Merrimack River Estuary, and to predict possible changes in these associations as a result of river diversion. In addition, a brief discussion of possible secondary effects of changes in plankton assemblages is presented.

1. Methods:

During April and October of 1971 surface and near-bottom plankton samples were collected on the flooding tide with a Clarke-Bumpus sampler equipped with a #20 mesh net. Selection of sampling sites during each sampling event (i.e., spring and fall) depended on prevailing salinities and thus on flows. Efforts were made to sample representative marine, estuarine, and freshwater habitats. Spring samples were taken at Stations 1, 3, 4, and 5, while fall samples were collected at Stations 2, 4, 5, 6, and 7. Temperature, depth, and conductivity were measured at each station with a Martek TDC Meter, periodically calibrated with a Beckman Salinometer (RS 5-3). Samples were preserved in neutralized formalin and later analyzed for species composition (Figure 14).

2. Results:

Twenty-two species, five genera, and at least seven higher taxa were identified from the spring plankton (Table XV). The phytoplankton was composed chiefly of diatoms, although dinoflagellates and chlorophytes were also present. All major phyla were represented in the zooplankton, with the calanoid copepods of the phylum Arthropoda numbering higher than other taxa. Approximately 65% of the zooplankton were holoplanktonic, spending their entire life cycle as plankton; the remainder were meroplankton or temporary plankton.

Diversity was greatest in the lower estuary (Station 3) where at least 20 distinct taxa were collected, and gradually decreased upriver. Only nine distinct taxa were collected at Station 5, the freshwater station. Species abundance at Station 1, just outside the estuary, was intermediate and similar to that of Station 4

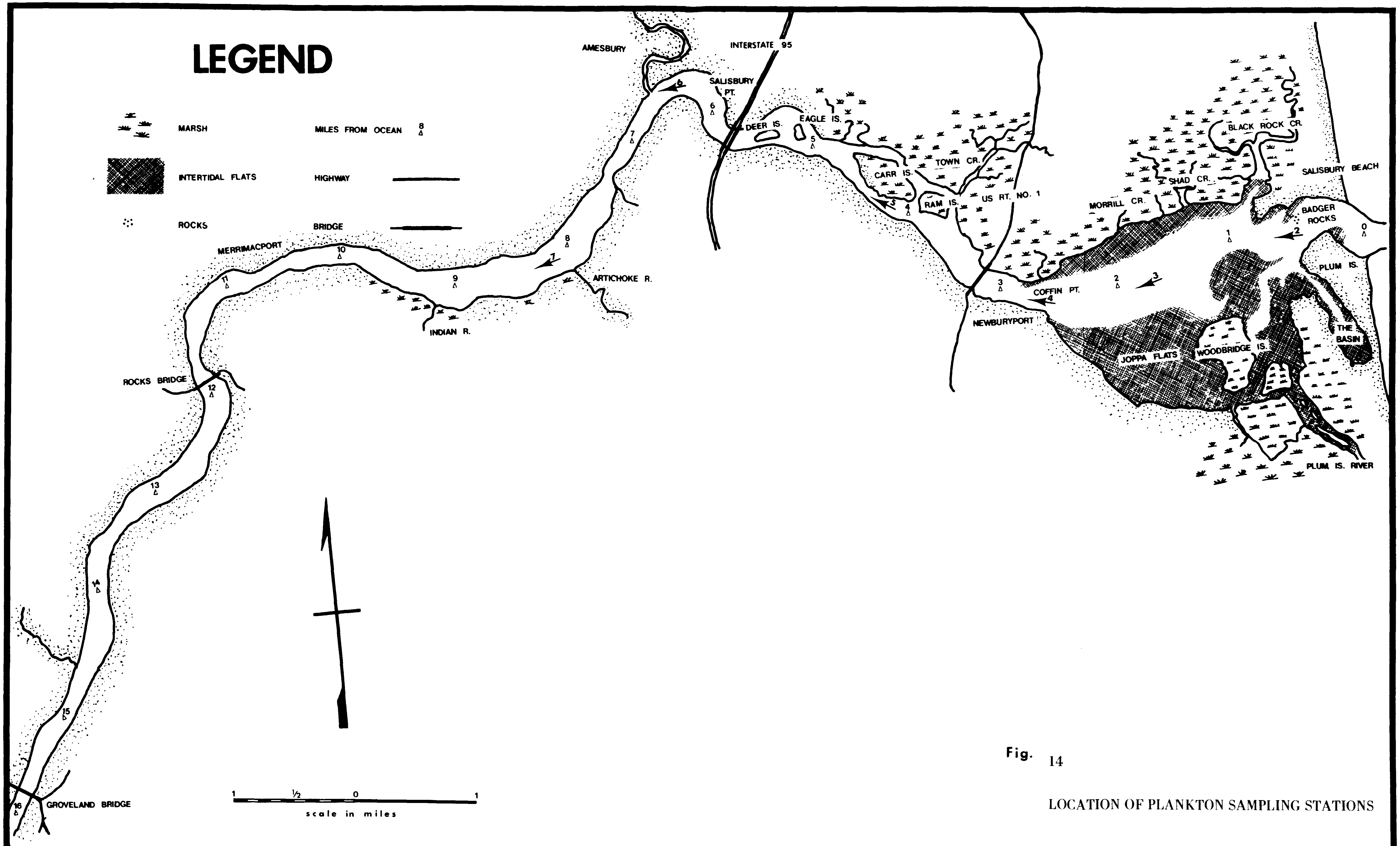


Fig. 14

LOCATION OF PLANKTON SAMPLING STATIONS

TABLE XV

SEASONAL DISTRIBUTION OF PLANKTON IN THE MERRIMACK RIVER ESTUARY, 1971

SPECIES	STATIONS SPRING	FALL	GEOGRAPHICAL DISTRIBUTION	
CHRYSOPHYCEAE:				
Coscinodiscus sp.	1,3,4,5	2,4,5	Cosmopolitan	Euryhaline
Thalassiosira gravida	1, 3			
Thalassiosira nordenskiodii	3			Benthic
Fragillaria islandica	1,3,4			Benthic
Fragillaria crotonensis		6, 7		Fresh, Benthic
Chaetoceros debilis	1, 3			
Chaetoceros convolutus	3			
Thalassiothrix nitzschioides	1,3,4			
Thalassiothrix fraunfeldii		6, 7		Fresh
Isthmia nervosa	3	2,4,5		Euryhaline, Benthic
Asterionella japonica	3, 4			Euryhaline to low brackish
Melosira moniliformis	4			Euryhaline, Benthic
Detonula confervacea	4			
Rhizosolenia sp.	4			
Navicula sp.	5			
PYRROPHYCEAE:				
Ceratium longipes	1, 3	2,4,5		Euryhaline
Ceratium fusus	3	2,4		Euryhaline
Ceratium tripos		2,4,5		Euryhaline
Ceratium bucephalum		2		Marine
Peridinium depressum	1,3,4	2,4,5	Cosmopolitan	Euryhaline
CHLOROPHYCEAE:				
Vorticella sp.	3,4,5			

(continued)

TABLE XV (continued)

SPECIES	STATIONS SPRING	FALL	GEOGRAPHICAL DISTRIBUTION
CHLOROPHYCEAE (continued)			
Closterium moniliferum		6,7	Freshwater
Pediastrum bivae	4	5,6,7	Fresh
Staurastrum dorsidentiferum		6, 7	Fresh
CYANOPHYCEAE:		6,7	
PROTISTA:			
Tintinnids	4, 5		
Parafavella gigantea		4	
Foraminiferans		2	
CNIDARIA:			
Hydromedusae		2	
ASCHELMINTHES:			
Keratella cochlearis	4, 5	6, 7	Fresh, < 4 $^{o}/oo$
Pleurotrocha sp.	1, 3		Euryhaline
Brachionus calyciflorous		6, 7	Fresh
Kellicottia longispina		6, 7	Fresh
Argonotholca foliacea		6, 7	Fresh
PLATYHELMINTHES:			
Rhabdocoels		2	
NEMATODA:	3, 4, 5	2, 5	Benthic
BRYOZOA:			
Cyphonautes larvae		2, 4	

(continued)

TABLE XV (continued)

SPECIES	STATIONS SPRING	FALL	GEOGRAPHICAL DISTRIBUTION	
MOLLUSCA:				
Gastropod veligers	1, 3	2, 4		
Gastropod juveniles		7		Fresh
Modiolus sp. (veligers)		2,4,5	Boreal Province & Virginian Province	Littoral to shallow, Euryhaline
Mytilus edulis (veligers)		2,4,5	Boreal Province & Virginian Province	Littoral to shallow, Euryhaline
Hiatella arctica (veligers)		4	Boreal Province & Virginian Province	Littoral to 183m
Other bivalve veligers		2,4,5		
Cerastoderma pinnatulum (juveniles)		2	Boreal Province & Virginian Province	6 - 183m
ANNELIDA:				
Spionid larvae	1, 3, 5	2,4,5		
Polychaete trochophores		2		
Other polychaete larvae		5		
ARTHROPODA:				
Calanus finmarchicus	3		Boreal Province & Virginian Province	Marine > 29 $^{o}/oo$
Pseudodiaptomus coronatus	3			0 - 23.9
Pseudocalanus minutus	1, 5	2,4,5	Boreal Province (circumpolar)	7.2 - 35 $^{o}/oo$
Paracalanus parvus		2	Cosmopolitan	Lit., Ner., > 14.8 $^{o}/oo$
Acartia clausi	1, 3	2,4,5	Boreal Province	Lit., Ner., 0 - 36 $^{o}/oo$
Acartia longiremus	3, 4		Arctic, Boreal & Virginia Provinces	Lit., Ner., 6.5 - 35 $^{o}/oo$
Acartia tonsa		2,4,5	Cosmopolitan	Lit., 0 - 30 $^{o}/oo$

(continued)

TABLE XV (continued)

SPECIES	STATIONS SPRING	FALL	GEOGRAPHICAL DISTRIBUTION	
ARTHROPODA (continued)				
Centropages typicus		2, 4	Boreal Province & Virginian Province	Neritic, > 30 $^{o}/oo$
Centropages hamatus		2	Boreal Province & Virginian Province	Littoral, Neritic, 1 - 31 $^{o}/oo$
Eurytemora herdmani		2,4,5	Boreal Province	Marine - brackish
Temora longicornis		2,4,5	Boreal Province & Virginian Province	Littoral, Neritic, 6.5 - 35 $^{o}/oo$
Oithona similis	1, 3	2,4,5	Cosmopolitan	7 - 38 $^{o}/oo$
Oithona nana		2,4,5		
Oithona juveniles		2,4,5		
Microsetella norvegica		2		Marine
Copepod nauplii	1,3,4,5	2,4,5		
Copepodites	1,3,4	2,4,5		
Podon intermedius	3	5	Boreal Province & Virginian Province	Euryhaline
Balanus nauplii	3,4,5			
Balanus cypris	1, 4			
Euphausiid calyptopis	1,3,4			
Corophium volutator	5	2	Boreal Province	Littoral, Euryhaline
Crangon septemspinosa larvae		2, 4	Boreal Province & Virginian Province	Littoral to 128m, Euryhaline
Philomedes sp.		5		
Ostracods		6		
ECHINODERMATA				
Ophiopluteus larvae	1, 3			

(continued)

TABLE XV (continued)

SPECIES	STATIONS SPRING	FALL	GEOGRAPHICAL DISTRIBUTION	
CHORDATA				
<u>Oikopleura dioica</u>		2,4,5	Cosmopolitan	> 11.4 $^{o}/oo$
Clupeid larvae	1,3,4			
<u>Fritillaria</u> sp.		2	Boreal Province	
Fish eggs	1, 3			

(Table XIV). Typically marine-estuarine assemblages were present in both surface and near-bottom samples from Stations 1 and 3 with estuarine diatoms, Chaetoceros debilis, Thalassiosira gravida, and Thalassiothrix nitzschioides, extremely abundant. A freshwater fauna was found in the surface water at Station 4, while both freshwater and estuarine organisms were present near the bottom. Samples from Station 5 contained primarily freshwater organisms such as Vorticella and Keratella cochlearis (Table XVI). A consistently greater number of individuals and taxon categories was found in near-bottom samples than in surface samples.

Thirty-three species, four genera, and at least nine higher taxa were identified in the fall plankton (Table XVII). The phytoplankton was composed of approximately equal numbers of diatom and dinoflagellate species plus two chlorophytes and one cyanophyte. Many species which had been extremely abundant during the spring, such as Chaetoceros debilis, Thalassiosira gravida, and Thalassiothrix nitzschioides, were no longer present. Most major phyla were represented in the zooplankton, and many new species, not present in the spring, were found. The number of species was by far highest among the calanoid copepods; rotifers and larvae of bottom invertebrates were also abundant. Approximately 75% of the zooplankton were holoplankton and 25% were meroplankton.

TABLE XVI

ECOLOGICAL STUDY - MERRIMACK RIVER ESTUARY - MASSACHUSETTS

DOMINANT PLANKTON AT EACH SAMPLING STATION DURING

SPRING

STATION	DOMINANT PLANKTON SPECIES
1	*Thalassiosira gravida*
	Chaetoceros sp.
	Chaetoceros debilis
	Thalassiothrix nitzschioides
	Fragillaria islandica
	Coscinodiscus sp.
	Ceratium longipes
	Peridinium depressum
3	*Thalassiosira gravida*
	Thalassiosira nordenskioldii
	Chaetoceros convolutus
	Chaetoceros debilis
	Thalassiothrix nitzschioides
	Fragillaria islandica
	Coscinodiscus sp.
	Asterionella japonica
	Ceratium longipes
	Ceratium fusus
4	*Fragillaria islandica*
5	*Coscinodiscus* sp.

TABLE XVII

ECOLOGICAL STUDY - MERRIMACK RIVER ESTUARY - MASSACHUSETTS

DOMINANT PLANKTON AT EACH SAMPLING STATION DURING

FALL

STATION	DOMINANT PLANKTON SPECIES
2	*Coscinodiscus* sp. *Ceratium longipes* *Ceratium tripos* *Oithona similis* *Oithona nana* Copepod nauplii Cyclopoid copepod juveniles *Acartia tonsa* *Temora longicornis* *Centropages typicus* Mytilid veligers
4	*Ceratium longipes* *Oithona similis* *Oithona nana* Copepod nauplii Cyclopoid copepod juveniles
5	*Oithona similis* *Oithona nana* Cyclopoid copepod juveniles
6	*Thalassiothrix fraunfeldii* *Fragillaria crotonensis* *Pediastrum bivae* *Staurastrum dorsidentiferum* *Keratella cochlearis* *Brachionus calyciflorous* *Kellicottia longispina*
7	*Thalassiothrix fraunfeldii* *Fragillaria crotonensis* *Pediastrum bivae* *Staurastrum dorsidentiferum* *Keratella cochlearis* *Brachionus calyciflorous*

Diversity was highest at Station 2 and gradually decreased upriver. The number of species and genera at Station 7, the last freshwater station, was approximately one-third that of Station 2. Stations 2, 4, and 5 contained marine-estuarine assemblages dominated by species of dinoflagellates, bivalve larvae, and copepods, whereas the assemblages at Stations 6 and 7 were essentially freshwater with *Fragillaria crotonensis*, *Thalassiothrix nitzschioides*, *Pediastrum bivae*, *Staurastrum dorsidentiferum* present in "bloom" proportions (Table XVII).

3. Existing Composition and Distribution of Plankton:

The overall composition of plankton in the Merrimack River Estuary is typical of large estuaries where, as a result of incomplete flushing, resident (i.e., marine and estuarine) plankton populations are maintained. In contrast, smaller estuaries with complete flushing contain a freshwater plankton assemblage during the ebbing tide [derived from adjoining river(s)], marine plankton assemblages during the flooding tide (derived from adjacent offshore waters), and no true estuarine plankton. Most species found in the Merrimack River Estuary were either boreal or cosmopolitan in distribution; none were uncommon in this latitude (Table XV).

Species composition within the estuary varied seasonally. Temperate estuaries are generally characterized by spring diatom blooms, which rapidly diminish and are replaced in summer by high numbers of dinoflagellates and meroplankton (Clarke, 1954; Johnson, 1957; and Odum, 1959). A lesser diatom peak occurs during the fall, followed by a winter low (Clarke, 1954). This cycle explains most of the seasonal "anomalies" in composition found in the Merrimack River Estuary. In this study, the majority of diatom species were found in the spring, while dinoflagellate species were dominant during fall. Generally, phytoplankton species present in April were not present in October, and vice versa. For example, the diatoms *Thalassiosira gravida*, *Fragillaria islandica*, *Chaetoceros debilis*, and *Thalassiothrix fraunfeldii*, were extremely numerous during April, but not found in the fall, and the dinoflagellates *Ceratium tripos* and *C. bucephalum* were collected in the fall, but not found in the spring. Many more species of copepods, rotifers, and molluscan larvae were found in the fall than in the spring and, as with phytoplankton, species present in the spring were usually not found in the fall and vice versa. For example, *Calanus finmarchicus*, a spring and summer species in the Gulf of Maine was collected only in spring, and *Centropages typicus* and *Acartia tonsa*, summer and fall species (Bigelow, 1924; Deevey, 1943 and 1946), were present only during the fall. *Pseudocalanus minutus* and *Oithona similis*, typically year-round copepod species, were found throughout the study period.

Horizontal species distribution within the Merrimack River Estuary varied seasonally, depending upon the amount of freshwater discharge. During the spring, when freshwater discharge was high, euryhaline marine and estuarine zooplankton were found upriver as far as Coffin Point. However, in the fall, when reduced river flow allowed saline water to intrude further, they were present beyond Carr Island.

Differential surface-bottom distributions of marine, estuarine, and freshwater species were noted in spring. In other words, marine and estuarine species were found farther upriver in bottom waters than in surface waters, and freshwater species extended farther downstream in surface waters. This is attributed to greater physical stratification within the estuary at this time. Differential surface-bottom distributions were not found during the fall when reduced flows caused vertical mixing.

4. Projected Changes as a Result of Diversion:

The net effect of river diversion will probably be a slight upriver shift of euryhaline marine and estuarine species during diversion, but this extension should not exceed that found during the low flow periods which occur naturally. This extension will affect the meroplankton to a greater extent than the holoplankton, in that holoplankters should merely oscillate about some zone farther upriver than present, but meroplankters which lead a benthic adult existence (e.g., clams), may encounter unsuitable substratum conditions when they settle. Since many of these benthic organisms spawn during the summer, extension of larval forms upriver, as well as possible temperature-salinity induced changes in estuarine adult reproductive patterns, should be considered if diversion, to an extent which would create below average flow rates during this period is anticipated. On the other hand, certain other meroplankters (barnacles, Mytilids, and wood-boring bivalves) may indeed find suitable habitat and thus extend their range upriver.

Although there will not be an upriver intrusion of saline water beyond areas that are now periodically affected by low level salinities, the areas between mile 1 and the mouth of the estuary will be under stronger marine influence. Present dominant euryhaline species in this region should not change, but marine species such as Calanus finmarchicus might extend farther into the estuary. It is not expected that new species will be introduced as a result of diversion.

In addition to a longitudinal effect, vertical distribution of plankton may also be disrupted since water stratification breaks down during periods of low flow. Thus, diversion could increase the amount of time organisms would be exposed to a homogeneous water column.

Furthermore, maintenance of a distinct salt wedge may be essential to continued estuarine residency for a number of plankters (Green, 1968). The magnitude of such an effect is in the realm of speculation however.

Finally, an upriver shift in plankton could result in an upriver shift of organisms which feed on plankton, for example, filter-feeding invertebrates, and some bait-size fish and fry of commercial species.

E. COMMERCIALLY IMPORTANT INVERTEBRATES

1. The Soft-Shell Clam, *Mya arenaria*

a. Importance to the Area:

The soft-shell clam, *Mya arenaria*, has played a major role in the economy of the Merrimack River region since colonial times, and is today the only commercially valuable shellfish living in the Merrimack River Estuary. Blue mussels, *Mytilus edulis*, are present at various locations, but are generally not utilized in the Merrimack River. A thorough review of the history of the clam fishery in this region is presented by Jerome, *et al* (1965).

Extensive intertidal mud flats located along both banks of the lower Merrimack River Estuary provide an excellent habitat for the soft-shelled clam, and these flats have not been seriously altered by dredging, filling, or other man-made physical changes. Pollution has been a serious problem since the mid 19th century, and while it has practically eliminated the soft-shell fishery, it apparently has not seriously affected the survival of the clams. In fact, the population of clams in the entire estuary is quite high. If totals for the Salisbury, Newburyport, and Newbury flats are combined, it is estimated that approximately 100,000 bushels of clams of legal or near-legal size are present, and with pollution abatement this could result in a total estimated wholesale harvest of $300,000.00 annually. Jerome, *et al* (1965) predicted that with proper management the harvest could exceed $500,000.00 and approach $1,000,000.00 annually.

In view of the tremendous future value of the clam fishery to the Merrimack River Estuary region, it is imperative that the potential effects of diversion on this resource be evaluated in detail before the idea proceeds beyond the planning stage.

b. Present Distribution and Abundance of Mya arenaria:

Mya arenaria is found in great abundance in the lower Merrimack River Estuary from near the mouth at Black Rocks and Newburyport Light upriver to Coffin Point several miles inland. Although considerable substratum suitable for clam settlement is found upriver of Coffin Point, no clams have been found or reported from this region.

A complete population count on all flats bordering the Merrimack River Estuary has been completed by Jerome, et al (1965) and a description of clam density in each flat is presented in detail in their report. Results of this study seem to indicate that distribution and abundance are not strictly controlled by the nature of the substratum or presence of H_2S, for clams were abundant in several grades of sediment and in varying amounts of H_2S. However, it is apparent from the pattern of distribution, summarized and represented in Figure 15, that abundance is greatest nearest to the mouth of the estuary, and decreases in the upriver direction. The Humpsand and Old Mussel Flats are an exception to this generality, but in these areas Mya abundance is primarily restricted by competition with Mytilus edulis.

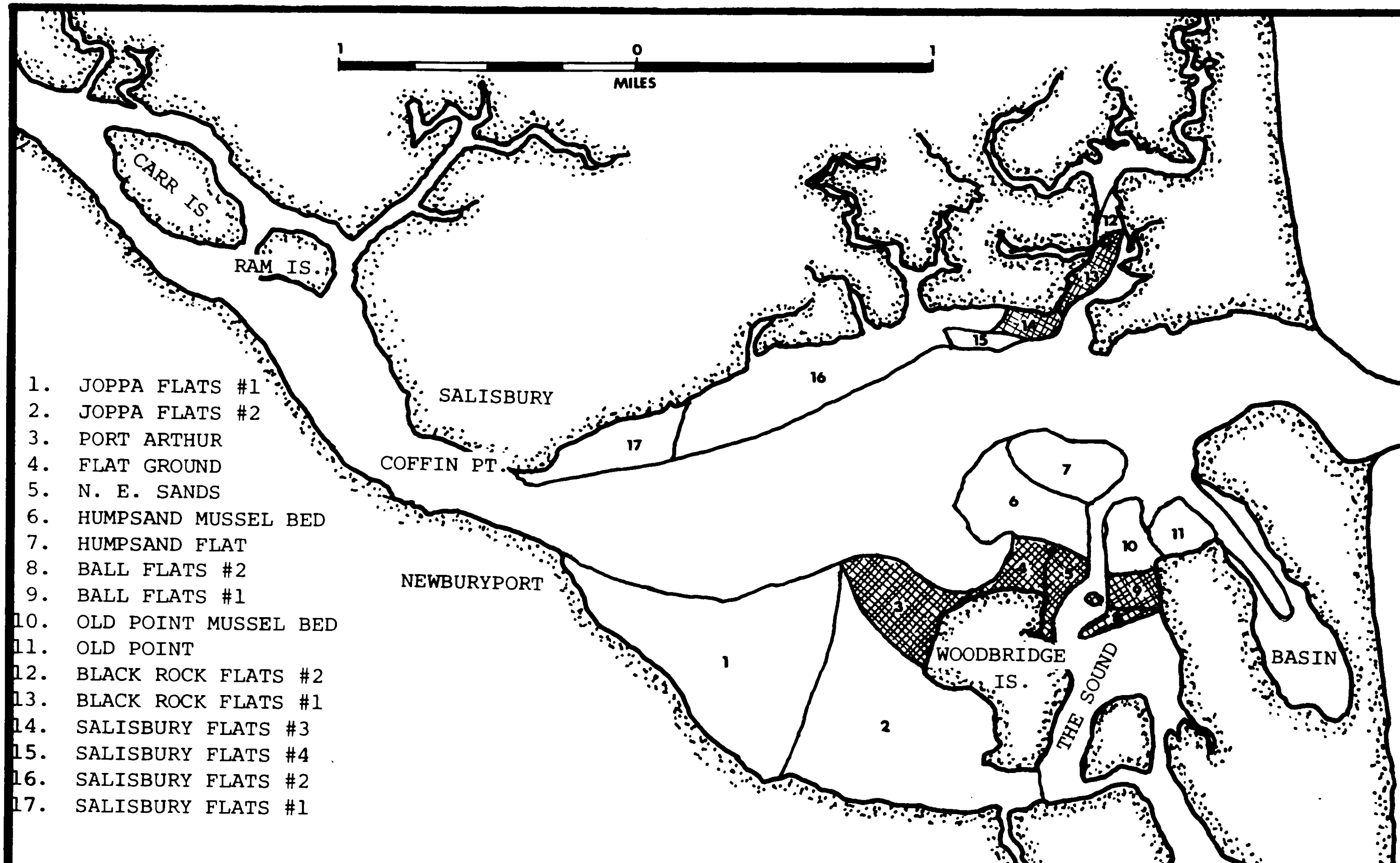


Figure 15. Soft-shell clam flats of the Merrimack River Estuary - (Shaded areas indicate highest abundance)

c. Potential Effects of Diversion on the Survival, Distribution, and Abundance of *Mya arenaria*:

A considerable amount of information is available on life history aspects of *Mya arenaria*, most of it being included in a bibliography by Pfitzenmeyer, *et al* (1960). While many aspects of *Mya* life history should not be noticeably affected by the potential diversion, certain physical changes brought about by decreased discharge could directly or indirectly present problems that would affect the survival of the clam population.

CHANGES IN SALINITY AND TEMPERATURE:

Mya arenaria occurs in the Western Atlantic from Labrador to North Carolina, and according to Pfitzenmeyer (1965) throughout its range it is tolerant of considerable variation in annual water temperatures and salinities. In the northern part of the range it is primarily a marine species, found in coastal inlets and bays in high salinity, while in more southerly areas it tends to become increasingly estuarine in habitat choice. Chesmore (1971, pers. comm.) has stated that in Massachusetts *Mya* is normally found in salinities above 15 $^{o}/oo$, and Hanks (1953) has shown that at Woods Hole, Massachusetts, the absolute minimum salinity at which a population can be established is 6 $^{o}/oo$, and below this salinity the clams will not remain buried in the sand.

Salinities vary drastically in the Merrimack River Estuary within each tidal cycle, and readings at Coffin Point, the presently observed upper limits of Mya distribution, range from near 0 $^{o}/oo$ during periods of high flow to above 30 $^{o}/oo$ when discharge is low. Since the clam is tolerant of such a wide range of salinity, it is unlikely that salinity increase will have any directly negative effect on its distribution and abundance. If any direct effect is observed, it is probably that abundance might increase in the presently low density portion (Stations 1 and 2) of Salisbury and Joppa Flats, primarily due to a reduction in the amount of time suboptimal salinities cover these habitats.

Within the normal salinity limits of the species, salinity variation does not appear to be a significant factor in the timing or success of spawning. Pfitzenmeyer (1965), Orton (1920), and others have shown that in New England the clam spawns continuously throughout the late spring, summer, and early fall. Time of spawning appears to be temperature regulated, beginning in April-May when waters warm to 10° - 12° C, continuing throughout the summer undiminished unless the temperature rises above 15° C, and terminating as temperatures cool in September and October. Because diversion should not result in significant temperature changes in the lower estuary, spawning should not be affected.

CHANGES IN SEDIMENTATION:

Alterations in sedimentation can seriously affect a benthic bivalve population, for few bivalves are capable of migration out of a heavily silted area. Along with others, Newcombe (1935) has demonstrated the limiting effect of shifting sand and silt-covered soft mud upon the growth of *Mya arenaria*, and Loosanoff and Tommen (1948) have shown that suspended silt in the water reduces the rate of feeding by oysters. As has been discussed earlier, a diversion of freshwater from the river could result in two potential changes in sedimentation. The first, a change in deposition of suspended sediments resulting from alteration of circulation, is unlikely to adversely affect the existing distribution and abundance of clams. Clams are presently abundant both over Joppa Flats, where sedimentation is very high, and over Salisbury Flats, where sedimentation rates are reported to be considerably lower (Hartwell, 1970). If the circulation pattern of the estuary does change over parts of the year when the critical low flow is reached, and if loss of stratification results in higher deposition over Salisbury Flats, it is probable that clams presently living there will survive just as they now do on Joppa Flats.

However, if a decrease in river discharge results in an increased accretion of the flood tidal delta, as Goldsmith (pers. comm.) has suggested may happen, then the possibility exists that some clam flats could be partly or completely covered over and smothered. However, the existing program of periodic maintenance dredging of the river channel should minimize this possibility. Further studies on rates of sediment inflow under reduced discharge would be needed to determine the extent of flood tidal delta migration.

POSSIBLE INTRODUCTION OF PREDATORY SPECIES:

Considerable research (much of it unpublished) has been completed on the biology of clam predators and methods of predator control. Several organisms have been reported to prey on *Mya arenaria*, among them the black duck, *Anas rubrupes*, but only three pose a definite threat to the survival of entire clam flats. The green crab, *Carcinus maenas*, appears to cause greatest year-round damage, followed in importance by seasonal destruction from the horseshoe crab, *Limulus polyphemus*, and lower sustained mortalities by the moon snails, *Polinices heros* and *P. duplicata* (Baptist, *et al*, 1957).

C. maenas and *P. heros* are present in low abundance near the mouth of the Merrimack River Estuary, but neither were observed on the clam flats during the 1971 sampling period, nor in the 1964 sampling by Jerome, *et al* (1965). Since these predators are presently causing damage to clam flats along other parts of the Northern New England Coast, it is important to determine if reducing discharge could lead to an immigration of these species onto the flats.

The green crab, *Carcinus maenas*, is presently found in considerable abundance in the tidal creeks along the lower end of the estuary and in the Basin area. In fact, Jerome, *et al* (1965) indicate that a minor green crab fishery has existed in the lower Merrimack River Estuary for years, but it has not been particularly successful, in view of the specialized pots required and low yield obtained. Most crabs caught commercially are used primarily as bait by southern New England and New York fishermen while fishing for tautog, Tautoga onitis. The green crab is not presently found in any abundance on the Merrimack River Estuary clam flats.

Because of the green crab's devastating effect upon the clam flats in other areas, much research has been done on its biology. A considerable amount of this material is found in unpublished reports of the U. S. Department of the Interior, Fish and Wildlife Service, Clam Investigations, but some have been published by Broekhuysen (1937), Scattergood (1951), and others. These reports contain some information relevant to the diversion study:

a) The green crab has been extending its range northward over the past century. Scattergood (1951) states that man's activities as well as drifting of the larvae and migration of the adults may be responsible for this northward spread. He further states that new populations will not be established unless environmental conditions are suitable.

b) Populations of green crabs in some years appear to be unlimited, but in others they are relatively scarce. Broekhuysen (1937) suggested that a combination of low temperatures and low salinities affect survival and distribution, especially in winter, and these factors account for fluctuations in abundance.

c) Goucher (1951) has reported catastropic mortalities of green crabs after the cold winter of 1931, and Broekhuysen (1937) and others have shown that green crabs eggs will not develop and hatch in salinities below 15 $^{o}/oo$.

Unpublished reports from the clam investigations and results of personal interviews indicate that the green crab is inhibited in some manner by low salinities and/or low temperatures. Obviously the crab is not restricted from the Merrimack River Estuary solely by low temperatures, for they thrive in colder waters in New Hampshire and Maine clam flats. Therefore, it is probable that the more important factor inhibiting migration onto the shallow Merrimack River Estuary flats is reduced salinities.

From this it is tempting to speculate that a decrease in river discharge will lead to conditions favoring a green crab invasion of the flats. However, no information is available to indicate whether periodic low salinities, such as those resulting from flood conditions, or continuous reduced salinities such as those observed in the river throughout most of the year, are more important in regulating distribution. If the flood is instrumental in limiting the crab, diversion should not affect the distribution. However, if reduced salinities throughout the year is the critical factor, any diversion other than flood skimming could favor crab dispersal onto the flats. Before a diversion scheme is decided upon, it would be desirable to run short and long term salinity tolerance tests to determine the conditions that would permit an expansion of crab habitats in the Merrimack River Estuary.

Polinices heros is an important predator on *Mya arenaria* in the Hampton-Seabrook Estuary, New Hampshire, and the Parker River - Plum Island Sound Estuary (Jerome, *et al*, 1965). However, no individuals of this species were found on the Merrimack clam flats throughout the study period, even though they were found at the mouth of the estuary. According to Minor (1950) and Hanks (1953) *Polinices heros* is a northern species normally found in high salinity waters. The snails cannot adjust to sudden changes in salinity (as little as 7 $^{o}/oo$) and react by complete withdrawal into the shell for four to five days. *P. heros* feeds normally at salinities of 32 $^{o}/oo$, but rates are reduced considerably at 18 $^{o}/oo$, and feeding terminates at 10 $^{o}/oo$, the salinity at which death eventually occurs.

Because of the species' inability to feed successfully in reduced salinity, it is probable that it is presently restricted from the Merrimack clam flats, at least in part, by this factor. If salinity is increased by diversion, a migration of snails onto the flats is possible. However, as in the case of the green crab, no definite conclusions can be made until it is known if the snail is affected more by low salinities of the spring flood or by low level freshwater intrusion throughout most of the year. If a continuous diversion is chosen, it would be desirable to determine the nature of the salinity factors now operating to limit distribution.

2. <u>The American Lobster, *Homarus americanus*</u>

According to Jerome, *et al* (1965) lobster fishing has been pursued for a long time by a small number of commercial lobstermen in the vicinity of the Merrimack River Estuary. No fishing is actually done within the limits of the estuary, but pots are placed in eight to ten fathoms outside the breakwater, in an area definitely influenced by the river. In addition to the commercial fishing, conversations with divers and local fishermen indicate that lobsters are also taken in fairly large numbers for home consumption by recreational pot fishermen and SCUBA divers.

Because lobsters are not taken within the Estuary, and since they are not dependent upon freshwater during any period of their life cycle, they should not be affected by the diversion.

3. <u>Crabs</u>

Three species of crabs have been periodically fished in the Merrimack River Estuary, the green crab, *Carcinus maenas*, has been discussed earlier. Two edible crabs, *Cancer borealis* (Jonah crab) and *Cancer irroratus* (Rock crab), are taken by commercial fishermen in limited numbers, but no fulltime fishing activity has been reported in the area. According to Jerome, *et al* (1965), over 2,000 edible crabs were taken in 1964 with a commercial value of $325.00.

Few crabs were seen throughout the sampling period, and from lack of data it is not possible at this time to make predictions on the effects of diversion.

F. FINFISH

1. Present Distribution and Relative Abundance of Finfish in the Merrimack River Estuary:

Jerome, et al (1965) completed an extensive year-long survey of the inshore fishes frequenting the Merrimack River Estuary from the ocean at Plum Island upriver to predominantly freshwater at the Artichoke River. Seine samples were taken monthly at five sites along the length of the Merrimack River Estuary (Figure 16), and the results of the sampling are tabulated in Table XVIII. Seventeen species of fish were captured, but only four species (American sand lance, mummichog, blueback herring, and alewife) comprised 99% of all fish captured.

The American sand lance was the most abundant species captured, but, as will be described later, it was not found in salinities of less than 25 $^{o}/oo$. Blueback herrings and alewives were abundant at all stations, and they tolerate a complete range of salinity variation, as does the mummichog, although the latter species was only found in

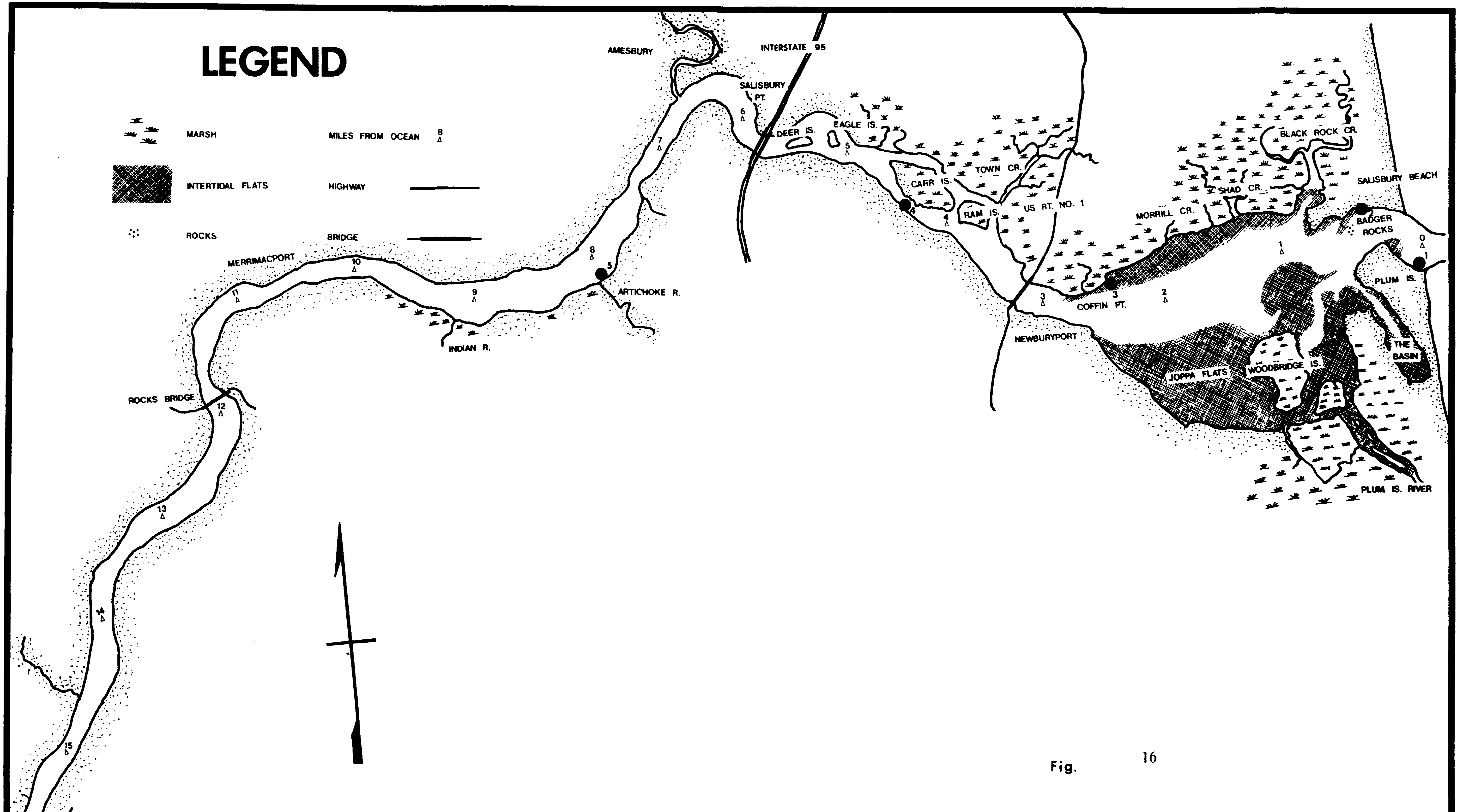


Fig. 16

LOCATION OF SEINING STATIONS
(Adapted from jerome, et al, 1965)

ECOLOGICAL STUDY
MERRIMACK RIVER ESTARUY - MASSACHUSETTS

TABLE XVIII

SURVEY OF 1964 MERRIMACK RIVER ESTUARY FISH SURVEY (Condensed from Jerome, et a!, 1965) - TOTAL NUMBER OF SPECIMEN CAPTURED PER THREE MONTHS, RANKED BY ABUNDANCE AT EACH STATION

	COAST GUARD COVE					BADGERS ROCKS					COFFIN POINT					CARR'S ISLAND					ARTICHOKE RIVER				
SPECIES	RANK	A	B	C	D	RANK	A	B	C	D	RANK	A	B	C	D	RANK	A	B	C	D	RANK	A	B	C	D
SQUIRREL HAKE	7			1																					
AMERICAN SAND LANCE	1		9120	4387	6768	2		10	12	1105	5		11												
THREESPINE STICKLEBACK	6		7			7			1		9		1												
AMERICAN SMELT	5			8		5			123		4			1	43	5		17		5					
ATLANTIC SILVERSIDE	4		1	25		4			99	68	5				11	4			51						
BLUEBACK HERRING	2			1132	219	1			1981	1761	1			4280		1		2	772	32	3			177	36
ALEWIFE	3			400		3			529	16	3			70		3		15	151	43	2		6	2036	6
MUMMICHOG						6		2			2		227	1976	76	2		133	140	10	1		9979	467	82
NORTHERN PIPEFISH											8			2											
WINTER FLOUNDER											6		1	3											
NINESPINE STICKLEBACK											9		1			8	1		1		9				1
WHITE PERCH											7		1		2	7		2	1	3	5			5	1
BLUEGILL											9		1								6		4	1	
AMERICAN EEL																6		2	5		7		1	3	
BROWN BULLHEAD																					8		2		
SPOTTAIL SHINER																8		2			4		14	20	
CARP																					9		1		

A = Janury, February, March B = April, May, June C = July, August, September D = October, November, December

SAMPLING OF EQUAL INTENSITY WAS NOT CARRIED OUT DURING ALL PERIODS OF THE YEAR.

high numbers at the upper three stations. Silversides and smelt were seasonally abundant at the higher salinity stations.

Carp, brown bullhead, spottail shiners, and bluegills were the only freshwater fish seined throughout the year, and all four species were taken at the Artichoke River stations.

Monthly trawl samples were taken at three stations, but only one was located inside the estuary. Of 19 species captured at all stations, only five species (the winter flounder, striped bass, pollock, sea hare, and lumpfish) were taken within the estuary. The winter flounder was the only fish taken in abundance at the inshore station.

A complete list of all species taken by various methods is listed by Jerome, *et al* (1965).

2. Potential Effects of Salinity Change on the Abundant Finfish Species, and on Species of Sport and Commerical Importance:

It is obvious that with the limited data at hand there is no way to accurately assess the total impact of a river diversion on all components of the finfish community. However, it is possible to make certain predictions on probable changes that could occur in the ecology of most abundant species, and in species of sport and commerical interest. Nine of these species are dicussed below. Most information on economic importance of each species has been obtained from Jerome, *et al* (1965). Unless otherwise indicated in the text, all information on life history has been adapted from Bigelow and Schroeder (1953).

a. THE SAND LANCE, *Ammodytes americanus*

IMPORTANCE TO THE AREA: The sand lance, *Ammodytes americanus*, is one of the most important fishes frequenting the Merrimack River Estuary. According to Jerome, *et al* (1965), this small fish has been used for food by many people during the past 60 to 70 years, but today the market is primarily for bait in the sport fishery, particularly in mackerel and tuna fishing. Considerable labor and special equipment are needed to harvest this fish successfully, and the sand lance bait industry is quite intensive during the fishing season from June through September. As a conservative value, it has been estimated that the total harvest of sand lance in the Merrimack River in 1964 was approximately 1,400 barrels.

Not only is the sand lance important as a commercial species, but is also serves as a main food supply for many sport fishes, including the striped bass, mackerel, and pollock, and as such, is of vital concern to the entire sport fishery in the Merrimack River Estuary.

PERTINENT ASPECTS OF LIFE HISTORY: Little is known of the biology of the sand lance, although Ohshima (1950) presents some biological notes on a Japanese species *A. personatus*. Bigelow and Schroeder (1953) and Norcross, *et al* (1961) state that there is only one species, *A. americanus*, but Richards, *et al* (1963) claim that there are in reality two species, *A. dubius* and *A. hexapterus*, readily separated by meristic characters and habitat preference. *A. dubius* inhabits offshore areas in which the salinity is usually above 30 ^{o}/oo, whereas *A. hexapterus* lives in inshore areas where the salinity fluctuates between 26 ^{o}/oo and 32 ^{o}/oo.

The lance is a schooling fish. It frequently congregates in dense schools along sandy foreshores and over the shoaler parts of the offshore fishing bank, but is seldom seen in rocky areas or on a muddy bottom. The lance has the unusual habit of rapidly burrowing several inches into the sand using its sharp snout, and in summer, during high tide, schools of lance swarm over sandy beaches above LW mark and burrow in, remaining there until the next high tide. It has been suggested that they spend most of their time buried in the sand, but it is not known if this habit is followed at all depths, or only in shallow waters. Adult sand lance feed abundantly on small crustaceans, fish fry, and worms. They, in turn, are a major source of food for such inshore fish as cod, haddock, halibut, silver hake, salmon, mackerel, striped bass, and bluefish.

Spawning in the American sand lance has not been directly observed, but it is probable that spawning activity begins in deep waters early in November. Norcross (1961) states that temperature must play an important role in determining the onset of spawning, and it is probable that most animals spawn when the water temperature drops to near 9° C. Hatching begins in late November, reaches a peak sometime after mid-December, and continues until mid-March. From plankton tows taken by Norcross (1961), few larvae were collected in water with salinities less than 30 $^{o}/oo$.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: The sand lance, probably *A. hexapterus*, congregates in dense schools in the extensive shallow sand and gravel areas at the mouth of the Merrimack River Estuary from spring through fall, and it is at this time that most harvesting occurs. They probably migrate to deeper waters in the fall and winter.

Even though sandy areas are found throughout the lower estuary, it is likely that the species is presently restricted from entering farther upriver by periodic wide fluctuations in salinity. Because of the intolerance of both species of lance for lowered salinity, it is probable that a reduction in freshwater outflow in the estuary could result in a net upriver increase in suitable habitat, and the possibility of an increase in the size of the resident population.

b. THE STRIPED BASS, Morone saxatilis

IMPORTANCE TO THE AREA: The striped bass, Morone saxatilis, is one of the most prized fishes caught in the Merrimack River Estuary, and according to Jerome, et al (1965), this fish is the basis of a sport and commercial fishery contributing many thousands of dollars and much recreational enjoyment to the towns along the lower Merrimack Valley. Thousands of local and visiting sportsmen fish from shore and boats during the months of May through October. Any legal sized fish (16" from the tip of the snout to the fork of the tail) may be kept by the fishermen, or may be sold if it has been taken by hook and line. Commercial fishing is reportedly on the increase, and an estimated 178,000 pounds of striped bass sold for $44,500.00 in 1964. This quantity was approximately half of the total harvest, and it is obvious that this fishery contributes significantly to the local economy through equipment sale and rental, food, and lodging.

PERTINENT ASPECTS OF LIFE HISTORY: Most aspects of the life history of the striped bass are well known, and the following report has been adapted primarily from data contained in Bigelow and Schroeder (1953). It is a relatively large, fast growing fish, a strong swimmer, and a voracious carnivore. Individuals have been known to live for more than 40 years, and to reach 125 pounds in weight. According to most reports, the striped bass is strictly an inshore fish, and is equally at home in fresh, brackish, and coastal waters. Most bass frequent the coast, but some run up into estuaries and river mouths. In some rivers they travel so far upstream that it is likely they remain all year.

Bass are active over a temperature range of from 43° to 70° F. Below 40° F they tend to become inactive, and mortality is high when fish are subjected to temperatures much above 77° F. The striper can tolerate a wide range of salinty.

The striped bass is a voracious carnivore, feeding on any available fish, chiefly herring, smelt, sand lance, eels, and silver hake in the Gulf of Maine. They also feed, exclusively at times, on squid, crabs, lobsters, and _Nereis_ (the clam worm), especially in estuarine situations.

Resident populations of striped bass migrate locally throughout the year. Most stripers travel in schools when they are undergoing migration, but individuals may be scattered while feeding in one general locality. Local migrations follow a seasonal pattern. In summer the fish school in feeding migrations near the surface of tributaries, bays, and coastal areas. In autumn the schools move into lower tributaries and bays for feeding and overwintering, and as winter approaches they concentrate in a somewhat less active condition in deeper water, mature fish ascend the rivers to spawn, and immature ones start their feeding migrations.

In addition to local migrations, some populations of the Atlantic Coast stock undertake coastal migrations. In late winter and early spring some striped bass from the mid-Atlantic states migrate to New England and remain all summer. In fall they may move south again, but more recent evidence indicates that the fish may just move offshore into deeper water for the winter.

The striped bass is anadromous, and will either spawn in brackish water at the heads of estuaries, or in freshwater farther upriver. There is no evidence of fish spawning in coastal waters. Those that enter freshwater may deposit their eggs only a short distance above the head of tide, or may run far upstream. Spawning appears to be governed primarily by water temperature (Nichols, 1966), and the peak of egg production occurs around 65° F. A spawning population may often consist of males, two or more years old, and larger females, four or more years old. One large female and several smaller males may often undergo common courtship. Spawning, when it does occur in the Gulf of Maine, usually occurs in the end of May or early in June, and the chief requirement for successful spawning appears to be a current turbulent enough to prevent the eggs from settling on the bottom where they could be covered by silt and suffocated.

The semi-buoyant eggs tend to slowly drift downstream with the current, and eggs that were produced far upriver may not hatch until they have reached tidewater. The eggs hatch in approximately two days at 65° F. Newly hatched larvae live in open freshwater and brackish water until they are 1/2 inch long, when they move toward shore and remain in schools throughout the first summer. Feeding habits of the young differ with age. Larvae feed on zooplankton, while the young consume small fish, worms, and other fleshy invertebrates.

During the second summer when the young are greater than six inches in length, they move down into bays and sounds, and begin feeding on small schooling fish, soft-shell clams, crabs, and clam worms. After the second year the young bass form denser schools and begin migratory patterns.

According to Bigelow and Schroeder (1953), the Merrimack River has never been an important overwintering ground for the striped bass, even though they are known to overwinter in the Parker River. There is no evidence of any spawning activity of the bass in the Merrimack River. In fact, the only area in the Gulf of Maine still utilized for spawning by the stripers are the Mousam Stream in Maine and the Parker River in Massachusetts. In recent years it has been sufficiently established that a great majority of the bass that summer in the western side of the Gulf come from spawning grounds to the west and south, probably from the Chesapeake and Delaware Bays, at an age of two to three years.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: Because the striped bass is equally at home in fresh, brackish, and coastal waters, and in light of the observation that the Merrimack River Estuary is neither a spawning area nor an important overwintering habitat, diversion of freshwater should have little observable effect on the ecology or biology of this important fish.

c. THE ATLANTIC SALMON, *Salmo salar*

HISTORIC IMPORTANCE OF THE SPECIES: During colonial times, salmon were found in every large stream not blocked by impassable falls. They were plentiful in the Merrimack River, and large numbers spawned in its upper tributaries, especially the Pemmigewasset, as late as 1793 (Lyman and Reed, 1866). However, the completion of the dam at Lawrence, Massachusetts, in 1847 completely blocked the salmon from the upper reaches of the Merrimack.

It was reported that for several years thereafter salmon congregated at the base of the Lawrence Dam in spring and summer, but there has been no run of salmon in the upper Merrimack since 1860, when the last salmon hatched above the dam had lived its life span. Salmon continued to enter the lower Merrimack River up to 1896, when there was a minor run in June and July. Many fish were observed at the Lawrence Dam, but only a few were lifted over.

According to Bigelow and Schroeder (1953), there has not been a single sea run salmon seen in the Merrimack River since 1901, although a few land-locked individuals have been reported in recent years.

PERTINENT ASPECTS OF LIFE HISTORY: Most aspects of the life history of the Atlantic salmon, *Salmo salar*, have been summarized by Bigelow and Schroeder (1953), and the following is adapted from their report. The Atlantic salmon generally lives the greater part of its life at sea and makes most of its growth there, but enters freshwater to spawn. Adults in the sea do not make extensive migration, but tend to remain localized not only within the coastal belt, but also within the zone of influence of the particular river system from which they came. This observation is strongly supported in the Gulf of Maine, where the fish appear about the mouth of rivers so soon after the ice has melted that they could not have come a long distance. The majority of Gulf Of Maine salmon become river mature considerably before the spawning season, but it is not certain if all salmon move inshore in spring, or only those that return to spawn. While none of the fish spawn before October, many enter freshwater as early as March and April, with the large runs occurring in June.

The salmon are silvery and fat when they begin their journey upriver, but once in freshwater they feed little and undergo extensive morphological changes. In smaller streams they may spawn only a short distance above the head of tide, but in large unobstructed rivers they may run upstream for more than 200 miles.

In the Gulf of Maine, salmon spawn in October and early November in sand and gravel stream beds. After spawning the spent fish are so weak that some of them die. Most of those that survive in small rivers return to the sea immediately, but those in large rivers sometimes overwinter and regain strength, returning to the sea the following spring.

The eggs are large and thick-shelled. They lie loose on the sand and gravel and develop slowly during the winter, not hatching until late April or early May. When the larvae hatch they carry a large yolk sac for nearly six weeks, and during this time they hide among pebbles, taking no food. When the yolk sac is absorbed the young, now called parr, commence to swim and feed. Parr live in freshwater for a variable amount of time, but generally move downstream from two to five years. The seaward migration begins any time from late spring to autumn, but most parr in the Gulf of Maine make the journey in June or July.

As the fish approach the sea they become silvery in color, and upon reaching saltwater become known as smolts. They remain for a time in river mouths and estuaries, but drop into deeper water with the onset of cold weather. The smolts grow rapidly when at sea, and may reach seven pounds after one year.

Salmon of all sizes are voracious predators in saltwater, feeding primarily on alewives, smelts, and mummichogs when they re-enter the estuaries to spawn. At times they also feed heavily on euphausid shrimp, pelagic amphipods, and sand fleas.

The salmon grow little in spawning years, and the size of a salmon depends more on the number of times it has spawned and on the date when it enters the river than on its age. There appears to be no specific pattern in spawning behavior. While some salmon return to spawn after one year at sea, others spawn only after up to five years at sea. No matter what the size or how often they spawn, few fish live to be older than eight or nine years in age from the time of hatching.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: State and Federal fisheries biologists in both New Hampshire and Massachusetts are formulating plans to restore natural runs of Atlantic salmon into the Merrimack River and its tributaries. According to Mr. Leigh Bridges of the Massachusetts Division of Marine Fisheries, a stocking program is essential to restore salmon runs to meet the spawning habitat's carrying capacity of 11,000 individuals per year. As with the shad program, potential problems that remain to be resolved include the threat of thermal pollution from projected power plants, present and future multi-purpose impoundments, lack of operational fish ladders, stream flow regulation, problems of canal entrapment, and stream bed gravel mining.

Minimum flow limits are extremely important to the success of this restoration program, for both the survival of smolts in their seaward migration and the success of spawning adults in reaching spawning grounds depend on a plentiful supply of freshwater at specific times throughout the year. The minimum flow required for successful restoration of the Atlantic salmon is presently being evaluated by the Bureau of Sport Fisheries and Wildlife, and others.

According to Bigelow and Schroeder (1953), yearly and seasonal differences in salmon fishing result from corresponding differences in numbers of smolts that reach seawater in any given year. The primary factor responsible for these differences is the height of the river water from summer to summer, or over periods of several summers. The river height is presently affected by yearly rainfall and present domestic and industrial use, and could be drastically affected by any future diversion plans.

When water is high, parr are protected from predation by kingfishers, mergansers, and other fish-eating birds, and are better able to escape trout predators, thus reaching the sea in great numbers. If the water is low, however, predation rates increase, fewer smolts reach seawater, and fewer then return as grilse or older fish.

Upriver migration is also regulated by stream flow. Salmon enter rivers in runs that are spaced irregularly in time, and vary in date from year to year, depending on the height of water in rivers and the strength of the current. Freshets tend to bring them in, but if the current becomes too strong, the fish simply hold position until currents slack. Fish that are in the estuaries remain there during periods between freshets, waiting for a pulse of freshwater to begin their migration, and salmon already in rivers are similarly quiescent during periods of low water and weak currents.

A minimum flow is also necessary to prevent stagnant areas and the resulting increase in temperature from insolation from developing in parts of the river during summer. Studies on Coho and sockeye salmon in the Bonneville Fish Hatchery in Oregon (Bouck, 1969) have shown that slight elevations in temperature increase disease and lead to high mortality in spawning salmon.

In view of the above, any diversion plan should consider the salmon restoration program, and the flows necessary to ensure its success.

d. THE SHAD, *Alosa sapidissima*

HISTORIC IMPORTANCE OF THE SPECIES: When the settlers first arrived in New England they found a seemingly inexhaustable supply of shad, *Alosa sapidissima*, annually running up all the large rivers and many of the smaller streams (Bigelow and Schroeder, 1953). The Merrimack River was especially noted for its abundance of shad, and it is reported that they formerly ascended for over 125 miles into Lake Winnepesaukee to spawn. The species very early became a staple item in the diet, and the demand increased as towns and cities sprang up. Efforts were made to intensify fishing to satisfy this demand, but the catch began to decline around 1800, and by 1896 only seven shad were reportedly caught in the whole length of the Merrimack River (Stevenson, 1899).

The decline has been attributed to pollution which rendered the river unsuitable for the species, to over-fishing which did not allow enough fish to spawn for replacement, and to the construction of dams which prevented fish from reaching spawning areas (Walburg and Nichols, 1967).

Today the shad is completely excluded from the Merrimack River, and the dam at Lawrence, only 20 odd miles upstream, stops any stray fish that may still enter the estuary.

PERTINENT ASPECTS OF LIFE HISTORY: Much information on the shad has been compiled by Bigelow and Schroeder (1953). The following is adapted from their reports. Like the alewife and other anadramous fish, the shad spends most of its adult life at sea, although it may enter brackish estuaries on occasion. While at sea the shad is a schooling fish, primarily feeding on plankton such as copepods, mysids, and larval barnacles. Individuals may also select bottom amphiphods on occasion.

Shad enter streams in spring and early summer when river water warms to 50° - 55° F. In the Gulf of Maine the heaviest runs are in May, with most spawning occuring in June. In large rivers the shad run far upstream, and take little or no food prior to spawning. Spawning occurs in sandy or pebbly shallows, where from 100,000 to 600,000 eggs are deposited. The emaciated spent fish depart immediately, begin feeding before reaching salt water, and have regained weight by the time they re-enter the sea.

The semi-buoyant eggs slowly roll on the bottom with the current, hatching in from 6 to 15 days, depending on temperature. Young shad remain in the river during the summer, feeding on insects and crustaceans, and grow rapidly. In the fall they depart for salt water and winter near the mouth of the parent stream.

Schools of adult shad are often seen inshore at the surface during spring, summer, and fall, but during the winter they disappear from these areas, heading out into deeper water. Shad undergo extensive migrations throughout the year, with large numbers of recently spawned individuals from both the Chesapeake area and from Canada moving into the Gulf of Maine for the summer and autumn.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: State and Federal fisheries biologists in both Massachusetts and New Hampshire have initiated plans to restore the shad fishery in the Merrimack River to its full potential. According to Mr. Leigh Bridges of the Massachusetts Division of Marine Fisheries, the spawning area as far north as Franklin, New Hampshire, should be able to support nearly one million shad, and initial stocking is expected to commence when present programs in the Connecticut River show signs of success. Problems that have to be resolved before this potential may be fully realized include the threat of thermal pollution from projected power plants, present and future multi-purpose impoundments, lack of operational fish ladders, stream flow regulation, problems of canal entrapment, and stream bed gravel mining.

For the success of this program, it is imperative that a minimum supply of freshwater be permitted over the dams throughout the year, and that a certain amount of this flow pass down properly designed fish ladders. The minimum amount of flow required for a successful shad restoration is presently being evaluated by the Bureau of Sport Fisheries and Wildlife, and others. Watson (1970) showed that temperature and percentage of river flow passing through the attraction channel, even during the increasing phase of upstream migration, were extremely important in determining numbers of Connecticut River shad passed over the Holyoke Dam, Massachusetts. A diversion then, even during peak periods of flow, may have some effect on spawning success of American shad, and downstream movement of juveniles may be affected also, although specific studies dealing with causal relationships behind juvenile movements are not at hand. Watson (1970) did suggest, however, that juvenile migration commences in September and continues through October in the Connecticut River, so extreme low water conditions encountered during summer months may not be of consequence.

e. THE ALEWIFE, *Alosa pseudoharengus*

HISTORIC IMPORTANCE TO THE AREA: Historically, large numbers of alewives entered the Merrimack River each year to spawn, and as late as 1896 when the alewife fishery was the subject of inquiry by the Bureau of Fisheries, catches large enough to be worthy of special notice were reported at the mouth of the Merrimack River. However, with the construction of dams and the increase in pollution resulting from industrialization, alewive runs declined precipitiously. Although few alewives enter the Merrimack today due to gross pollution and physical obstructions, fishways recently constructed at Lowell, Massachusetts, facilitate their ascent, at least this far. Projected pollution abatement schedules and construction of additional fishways give promise of potential comeback of this species in the future.

PERTINENT ASPECTS OF LIFE HISTORY: (Excerpted from Bigelow and Schroeder, 1953.) The alewife is an anadromous fish, and with the exception of spawning season, the adults spend all of their time at sea. Alewives are chiefly plankton feeders, with some evidence of selectivity for copepods, amphipods, shrimp, and appendicularians. They may also take small fish such as herring, eels, sand lance, and cunners.

Alewives enter small streams in April to spawn, and while the species is very general in choice of stream, it is believed that individuals return to the stream in which they were hatched. The alewife is more successful than the shad in surmounting fishways of suitable design, and in large rivers the fish may run far upstream. Most individuals do not eat when they are going upstream.

Sexually mature adults spawn in ponds and sluggish stretches of streams, but never in swift water. Spawning lasts only a few days, and then spent fish return downriver immediately thereafter. Adults make the rapid change from saltwater to freshwater and back again without damage, but the strain of spawning leaves the fish thin. They feed ravenously on shrimps and other small organisms upon entering brackish water, and recover rapidly when they enter the sea.

Spawning occurs at 55° to 60° F, and the juveniles hatch in approximately five days at this temperature. They begin to descend the stream as early as June 15, continue all summer, and by autumn the two to four inch young are in saltwater, and remain there until sexual maturity.

At sea alewives are gregarious like herring, and a given school maintains its integrity for extended periods of time. It is likely that the majority remains in the vicinity of the freshwater influence of stream mouths and estuaries from which they came, although individuals have been found as far out as the banks.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: Even though few alewives presently enter the Merrimack River, a comeback potential does exist for the species if properly designed fish ladders are constructed and pollution is lessened. Though adult upstream migration occurs in spring when flows are usually high, presumably alewives exhibit rheotaxes similar to the shad and may require similar attraction velocities. Young alewives on the other hand may be more susceptible to low flow conditions during the summer since they descend the river throughout this period and may experience high mortality due to inability to go over dams or bypass them, except via turbine intakes.

As in the case of the shad and salmon, the success of restoration of this valuable fishery depends on strict adherence to minimum required flows arrived at through consultations with biologists involved in state and federal anadromous fisheries programs.

f. THE BLUEBACK HERRING, *Alosa aestivalis*

According to Bigelow and Schroeder (1953), the blueback herring, *Alosa aestivalis*, is nearly identical to the alewife both in physical appearance and in life history. There are some minor differences in breeding habits, including runs later in the season when the water is warmer, and spawning shorter distances upriver. Because of the apparent similarities in the biology of these two species, conclusions drawn from the alewife should also pertain to the herring.

g. THE ATLANTIC MACKEREL, *Scomber scombrus*

ECONOMIC IMPORTANCE TO THE AREA: According to Jerome, *et al* (1965), mackerel fishing is one of the chief sport attractions in the Plum Island area. Mackerel often arrive at the mouth of the estuary in late spring or early summer, and they are intensively fished by private, party, and charter boats from this time until their departure in fall. The mackerel fishery forms the main-stay of the party boat business in summer, and contributes thousands of dollars to the economy of the area each year.

PERTINENT ASPECTS OF LIFE HISTORY: The mackerel is an open ocean fish, and while small individuals may enter estuaries and harbors in search of food during the summer, they never enter freshwater. Mackerel appear in great numbers inshore as temperatures rise, and they remain close to the surface to feed for indefinite periods of time during the summer. With the onset of colder temperatures the mackerel migrate to deeper offshore waters. Most aspects of life history, including feeding, spawning, and larval development, take place in open ocean waters.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: The mackerel often appear in great numbers at the mouth of the Merrimack River Estuary and adjacent areas around Plum Island, possibly to feed on locally abundant marine organisms such as sand lance and clam worms. Since freshwater diversion should not diminish the abundance of these or any other primary prey species, no effect on the local mackerel fishery should be evidenced.

h. THE WINTER FLOUNDER, *Pseudopleuronectes americanus*

ECONOMIC IMPORTANCE TO THE AREA: According to Jerome, *et al* (1965), the winter flounder, *Pseudopleuronectes americanus*, is one of the most important sport and commercial fishes found in the Merrimack River Estuary. Most of the present day commercial catch is taken in the open ocean using otter trawlers, but an extensive sport fishery occurs over the shallow flats and deeper channels of the Merrimack River Estuary, and in its tidal tributaries. No estimate of the size of the sport catch has been made, but it is believed to be large.

PERTINENT ASPECTS OF LIFE HISTORY: The winter flounder is the commonest and most familiar bottom fish found in the Gulf of Maine. Bigelow and Schroeder (1953) indicate that it is a cosmopolitan species, running from the intertidal in estuaries up to freshwater, and going as deep as 70 fms in the open ocean. Smaller fish are usually found in shoal water, and larger ones tend to live deeper. The winter flounder usually lies on the bottom buried in sand or mud, with all but the eyes covered, and darts out rapidly to capture prey. Most spawning occurs in deep water where salinities are above 30 $^{o}/oo$, but some spawning individuals are reported in estuaries in one to three fms of water and salinities as low as 11 $^{o}/oo$. The eggs are non-buoyant, and sink to the sandy bottom, where they hatch in from 12 to 14 days. Metamorphosis occurs rapidly, and the young fry soon change from a diet of diatoms to crustaceans and other small invertebrates.

POTENTIAL EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: The winter flounder spawns over a wide range of salinities, and it is generally considered to be euryhaline throughout its life. However, although periodic increases in salinity of the estuary are not expected to have any marked affect on this species, recent evidence has shown that winter flounder exhibit a definite preference for estuarine waters during parts of their life cycle (Frame, 1972).

i. THE AMERICAN EEL, *Anguilla rostrata*

ECONOMIC IMPORTANCE TO THE AREA: The American eel, *Anguilla rostrata*, played an important role in the economy of the Merrimack River Valley region in the past, when it was in demand as a food or table fish (Jerome, *et al*, 1965). Significant numbers of eel were taken in pots placed in the tidal portions of the Merrimack River, and up to 7,000 pounds per week were shipped to markets in Boston and New York. The fishery has undergone a precipitous decline in recent years, primarily due to a reduction in demand, and by 1964 only 3,000 pounds per year (with a total value of $540.00) were taken for both food and bait. The primary use of eels today is as live bait for the striped bass fishery.

PERTINENT ASPECTS OF LIFE HISTORY: Many aspects of the life history of the American eel have been unknown until recently, but it is now certain that the species is catadromous; that is, it spends most of its life in fresh or estuarine waters, and returns to the deep sea to spawn.

(The life history of *Anguilla rostrata* is adapted from Bigelow and Schroeder, 1953.)

Young elvers, two to three and a half inches long, appear in coastal waters in spring, and invade all waters entering the Gulf of Maine. Some elvers settle in tidal marshes and harbors, and some even remain in protected coastal areas, especially if there is *Zostera* present. Most, however, enter freshwater, and many go up into the fartherest reaches of the river. They can live and thrive wherever food is available, and can tolerate the whole spectrum of salinity and a wide range of temperature. No animal food, living or dead, is refused, and the diet depends on what is available.

American eels are chiefly nocturnal in habit, but they are often seen during the day. They grow slowly, and may take ten to twenty years to mature. At the onset of sexual maturity in the fall, the eels that are living in freshwater move downstream, cease to feed, and undergo physiological change. Individuals living in estuarine conditions undergo the same changes, and all mature individuals of both sexes then move out to sea, where the ovaries of the female begin to ripen.

After leaving the shore the eels disappear and it is believed that they re-appear in the Sargasso Sea, one to two months later.

They spawn in mid-winter, and die immediately thereafter. The eggs float until hatching into a leptocephalus stage, and metamorphosis takes place a year later after the leptocephali have migrated to offshore waters. After metamorphosis, the elvers continue their migration to shore.

PROJECTED EFFECTS OF DIVERSION ON THE ECOLOGY OF THE SPECIES: The American eel was found in low numbers throughout most of the study area, and Jerome, *et al* (1965) found it living in salinities ranging from 0.0 $^{o}/oo$ to 18.0 $^{o}/oo$.

Because the American eel is extremely tolerant to both salinity and temperature variation, and considering the wide variability of food eaten, there is no reason to believe that diversion of freshwater from the Merrimack River would have any effect on its distribution and abundance.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

VI. POTENTIAL EFFECTS OF DIVERSION ON THE PARKER RIVER ESTUARY AND THE PARKER RIVER NATIONAL WILDLIFE REFUGE

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

VI. POTENTIAL EFFECTS OF DIVERSION ON THE PARKER RIVER ESTUARY AND THE PARKER RIVER NATIONAL WILDLIFE REFUGE

Major tidal channels have a significant influence on estuarine circulation patterns, and the Plum Island River (Figure 1) is the largest major tidal channel in the region (Hartwell, 1970). It connects the Merrimack River Estuary with the Parker River Estuary and flows through the heart of the Parker River National Wildlife Refuge. Because Refuge wildlife are attracted to the area by the richness of the estuarine waters of the Plum Island River, it is important to determine if the Merrimack River contributes substantially to these waters.

The Plum Island River is very shallow in places, and numerous sand and mud flats restrict flows between the systems to a minimum except at highest tides. Hartwell (1970) has shown that even though there is considerable hydraulic exchange between the two estuaries, the nature and orientation of sand bars and spits indicate that ebb-tidal currents flowing from the Parker River Estuary into the Merrimack River Estuary are dominant over flood currents passing in the reverse direction. In addition, a study of the charts prepared by Hartwell

(1970) and results of discussion with Goldsmith (1971) indicate that the interface between the two water masses tends to oscillate back and forth with each tidal cycle resulting in little net exchange between the systems. Therefore, in spite of the connection between the two systems, we have found no evidence to indicate that changes in salinity in the Merrimack River Estuary will affect the Refuge. Mr. Edward Moses, Director of the Parker River National Wildlife Refuge, has concurred in this belief.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

VII. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

VII. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY OF MAJOR ELEMENTS STUDIED

1. Salinity Study - Mathematical Model:

The mathematical model used to investigate the effects of diversion on the salinity of the Merrimack River is based on the salt-balance equation of Pritchard (1959), as modified by Boicourt (1968). This model was selected because it was the most realistic model that could be used, consistent with the input data available.

The results of the study are presented as a graphical atlas of the salinity distribution along the longitudinal axis of the estuary. Each entry in the graphical atlas represents the effect of given diversion at various river flows. The effects at both low and high tide are considered.

The limits of salt intrusion vary from 7 Km (4.3 statute miles) to 17.5 Km (10.9 statute miles) from the mouth, representing river flows from 16,000 cfs to 800 cfs, respectively for the high tide case. For the low tide case, the limits of salt intrusion vary from 5 Km (3.1

statute miles) to 11 Km (6.8 statute miles) from the mouth, representing river flows from 16,000 cfs to 800 cfs, respectively.

The model is found to agree reasonably well with the results of measurements over the range of flow rates investigated. The model over predicts slightly under some conditions based on the limited experimental data available for verification; more data or verification would be of value for the lower flow rates. Since the coefficient determining the diffusion rates are based on the input data, the use of the model outside the range of validation should be done with caution.

2. <u>Potential Effects of Diversion on the Physical Characteristics of the Estuary</u>:

a. Longitudinal Changes in Salinity Distributions and Alterations of Estuarine Conditions.

The Merrimack River Estuary is essentially fresh throughout most of the tidal cycle, but saline water progresses further upstream as discharge drops. While natural flows rarely drop below 800 cfs (control level established for October through May) on an average weekly basis, the daily operational pattern of the several dams along the Merrimack River is such that flows fluctuate markedly within a week. This is reflected in monthly averages of daily minima which are in fact below control levels during summer and early fall months.

With this fluctuation in mind, we may say that although certain stretches of the river may be subjected to more frequent saline influence due to diversion, this should not represent an entirely new experience. Increased time of exposure to particular salinities would depend upon flow rate, and for the range of diversions considered here (100 to 2,000 cfs), this time would be minimal under peak dischange and greater as flows decrease.

Seasonal patterns of longitudinal salinity distribution are markedly different due to amount of discharge, yet within any given season the pattern is displaced only 1/2 to 1 and 1/2 miles upstream at the highest rates suggested. Salinity encroachment at control levels is higher, ranging from 2 to >5 miles upstream depending upon season, but intrusions this far and further upriver do occur periodically under extreme low flow conditions.

Tidal oscillations produce changes in the longitudinal salinity pattern amounting to approximately 4.5 miles (7 to 8 Km). Such changes would persist with diversion, but oscillations would merely be about a node further upstream.

Additional effects which diversion may have upon the Merrimack

River Estuary have to do with circulation patterns, and, in turn, their effect on certain other physical parameters. Workers have shown that vertical stratification in the estuary depends upon river discharge (i.e., under low flow rates the estuary becomes progressively more well-mixed). Such changes must be considered as they relate to the ecology of the area.

b. Alterations in Suspended Sediment Distribution

Ocean water entering the estuary carries less sediment than river water. When Merrimack River flows are high, most sediment is flushed out of the estuary, but as discharges drop to normal levels and stratification develops, sedimentation becomes heaviest over Joppa Flats. When stratification breaks down under summer and fall low flows, sedimentation tends to occur rather evenly throughout the estuary.

1) Diversion of freshwater will reduce the total load of suspended sediments brought into the estuary, but at the same time will also lower the flushing rate, possibly resulting in a net increase in deposition. Because of changes in circulation brought about by lower flows, deposition should generally be reduced over Joppa Flats, and somewhat increased throughout the rest of the estuary.

c. Net Inflow of Bottom Sediments Resulting from Changes in Current Flow

Current velocities entering the Merrimack River Estuary on the flood tide tend to be considerably stronger than those leaving on the ebb, and these currents are active in the formation of a flood tidal delta through a net influx of sediment into the estuary.

The flood tidal delta at the entrance to the Merrimack River Estuary is at present relatively stable. Goldsmith has suggested that a reduction in river discharge could lead to an increased rate of sediment movement, and a net migration of the flood tidal delta into the estuary. This could result in changes in circulation within the estuary through clogging, and increased erosion along Plum Island. Continual dredging to remove sediments would alleviate the first problem.

d. Upper Estuarine Temperature Changes

Daily and seasonal temperature variability in river water is generally more pronounced than in ocean waters, with summer temperatures warmer and winter temperatures colder. Because of this, freshwater diversion could affect the temperature characteristics of the Merrimack River by leading to a reduction in temperature fluctuations in the upper estuary, and to summer low flow/high temperature conditions in the freshwater river. Further studies are suggested to determine the extent of the latter.

e. Changes in the Effect of Pollution Load

Because of domestic and industrial pollution, dissolved oxygen readings presently drop to critical levels under low flow/high temperature conditions in late summer and early fall. It is probable that unless pollution is abated, diversion during this time period may further aggravate the situation.

3. Potential Biological Changes Resulting From Diversion:

a. Intertidal Plants

Compared with other estuarine environments, plant species diversity is low in the Merrimack River Estuary. At least 37 taxa of vascular plants are found in the estuarine portion of the river, with 14 species widely distributed and the remainder only occurring sporadically. Twenty-eight taxa of algae are found in the same region, but only the green algae are cosmopolitan throughout the study area.

Preliminary observations indicate that distribution is primarily controlled by presence or absence of suitable substrata, salinity, sedimentation, and pollution load. No vascular plants are found at the lower stations, primarily due to the absence of suitable substrata.

With progression upriver, rocky shores give way to mud and sand, and the number of intertidal vascular plants increase, until reaching greatest diversity at Stations 18 through 20. Beyond this point salt water species drop out and are replaced by typically freshwater species. No salt water species are found above Station 28.

As opposed to the vascular plants, maximum numbers of algae are found in the lower estuary. These plants rapidly diminish in numbers above Station 6, and show a progressive dropping out of species with upriver progression until none are found above Station 26.

One of the principle effects of diversion should be an alteration of the delicate balance between freshwater, brackish water, and salt water species, evidenced by changes in distribution and abundance. An increase in salinity resulting from diversion would probably allow upriver movement of marine or estuarine algae such as _A. nodosum_ and _F. vesiculosus_, and therefore alter existing community composition. Typically estuarine vascular plants such as _Spartina_ spp. would also go further upriver and replace freshwater species. Other changes in plant communities, as yet undefined, may result from alteration of current flow and velocity, changes in sediment transport and patterns of deposition, reduction of seasonal temperature variation, and changes in pollution load. Further studies would be needed to determine the nature of these changes.

b. Intertidal Invertebrates

Forty-seven species of invertebrates were collected in the Merrimack River Estuary during the sampling period. Sixteen species were only found outside the harbor entrance, 26 were found in the estuary proper, and five species were restricted to the freshwater river. Of the 26 species living within the estuary, 19 were euryhaline marine organisms, four were true estuarine organisms found exclusively in the estuarine environment, and three were freshwater species capable of withstanding periodic low salinities.

The distribution of intertidal invertebrates in the Merrimack River Estuary exhibit a definite progression of invertebrate associations extending from the open ocean to the freshwater river. These associations, and their approximate locations in the river, can be roughly classified as stenohaline marine (open coast), euryhaline marine (0-1 miles upriver), true estuarine (1-5 miles upriver), impoverished freshwater (5-9 miles upriver), and freshwater (above 9 miles).

The marine association contains the highest number of species found at any location in the estuary, and approximately 75% of these species are stenohaline (intolerant of lowered salinities). The euryhaline marine association just upriver contains far fewer species, and is in reality an impoverished extension of the open ocean community. All organisms living in this region are generally found in the oceanic environment, but in contrast to stenohaline forms, they are capable of surviving periodically reduced salinities.

In the estuarine zone extending from miles 1 through approximately 5, five species of true estuarine marine species and a few salt-tolerant freshwater species. As one progresses upriver, the euryhaline marine organisms rapidly drop out, and the association becomes dominated by true estuarine species. Salinity fluctuations in this area are drastic, and during periods of low flow, mobile euryhaline marine species will migrate into the area, producing a noticeable increase in species numbers. These species are generally unable to establish permanently, however.

The estuarine fauna becomes progressively reduced from miles 5 through 9, and increasing numbers of salt-tolerant freshwater species begin to appear. Salinities are too low for most estuarine species, and periodically too high to permit establishment of typical freshwater species. Because of the severity of these conditions, along with the effects of pollution and sedimentation, this region presently represents the most unsuitable habitat in the Merrimack estuarine system.

Species diversity increases in the freshwater zone beyond mile 8, but it is still well below that found in other rivers of comparable size, due to the combined effects of pollution and sedimentation.

The stenohaline marine association should not be affected in any manner by freshwater diversion, since the habitat presently is under little influence from the estuarine environment. Some changes in species composition, however, may occur in the euryhaline marine zone. It is likely that with an increase in salinity there will be a net migration of several additional marine species into the area, and an increase in abundance of some species already there. An introduction of these species should not lead to interspecific competition, since they presently exist outside the estuary.

More significant changes could occur in the estuarine zone, the net effect of which would undoubtedly be to increase the total number of species. There should be a net upriver migration of several species along the length of the estuary in response to increased salinity. In the lower estuary, this shift could bring euryhaline marine organisms into the area now occupied by estuarine species. In addition, if algal and vascular plant growth is enhanced either through increased salinities or decreased sedimentation, as has been suggested previously, it is possible that intertidal invertebrates now feeding or living on these plants in the lower zones will move into this area to fill the newly established niche. In the upper estuary, some salt tolerant freshwater species, now present in low abundance in the upper reaches of the estuarine zone, may shift further upriver with increased salinities.

Any change in the impoverished freshwater zone will probably be beneficial. It is now in a serious state of ecological stress due to a combination of pollution and low level salt intrusion. A decrease in river discharge would probably permit migration of some estuarine species into this area, but should have little effect on the few salt-tolerant freshwater species existing there in low abundance, since they are presently found in higher salinities downriver. If diversion is preceded by a decrease in pollution, followed by an increase in oxygen and a reduction of sedimentation, a further enrichment of the fauna in this habitat would result.

No migration of estuarine organisms into the freshwater zone is possible, since the salt water, after diversion, would not intrude beyond the limits presently reached.

c. Subtidal Benthic Invertebrates

The results of benthic sampling demonstrated that the benthic fauna of the Merrimack River Estuary is extremely limited in species numbers. Eighteen species of bottom invertebrates were found during the sampling period, but only 15 were collected alive. Of these species, three were marine, three were truly estuarine, and the remainder were typically freshwater. The largest number of species was found at the freshwater stations above mile 12, while no living organisms were collected at three of the estuarine stations. Diversity was extremely low at the remaining stations.

Because of this low species diversity throughout the estuary, resulting from a combination of factors, it is difficult to hypothesize on the effects of diversion. The existing maximum upriver intrusion of salt water will not change, so unless abatement of pollution produces more optimal conditions, an increase in species diversity in the freshwater zone should not occur. However, the portion of the estuary now subject to salt intrusion will be saline more often, probably resulting in a net upriver migration of some estuarine and marine species, particularly those with larvae now existing as plankton in the Merrimack River Estuary. The extent of the upriver migration cannot be predicted at this time.

d. Plankton

The overall composition of plankton in the Merrimack River Estuary is typical of large estuaries where resident plankton populations are maintained as a result of incomplete flushing. At all times plankton species diversity was greatest in the lower estuary, and lowest in the upper. Typically marine-estuarine assemblages were found in surface and near-bottom tows from the lower estuary, but estuarine organisms were only found in bottom tows in the upper estuary. Surface tows contained only freshwater species at these stations. A consistently greater number of individuals and taxa categories was found in near-bottom samples than in surface samples.

The net effect of river diversion will probably be a slight upriver shift of euryhaline marine and estuarine species during diversion, but this extension should not exceed that found during the low flow periods which occur naturally. This extension will affect the meroplankton to a greater extent than the holoplankton, in that holoplankters should merely oscillate about some zone farther upriver than present, but meroplankters which lead a benthic adult existence may encounter new substratum conditions which may be unsuitable for some, but which may induce settlement of others, leading to an upriver extension of their range.

Although there will not be an upriver intrusion of saline water beyond areas that are now periodically affected by low level salinities, the area between mile 1 and the mouth of the estuary will be under stronger marine influence. Present dominant euryhaline species in this region should not change, but marine species might extend farther into the estuary. An upriver shift in plankton communities could result in an upriver shift of organisms which feed on them. It is not expected, however, that new species will be introduced as a result of diversion.

In addition to longitudinal effects, vertical distribution of plankton may also be disrupted since water stratification breaks down during periods of low flow.

e. Commercially Important Invertebrates

The soft-shell clam, Mya arenaria, is the only commercially valuable shellfish in the Merrimack River Estuary. Because of pollution in the river, this valuable resource is not presently utilized. However, it is estimated that with proper management the harvest could approach one million dollars annually.

The effects of diversion upon the soft shell clam center upon possible changes caused by salinity and sedimentation patterns. Since the clam is tolerant to a wide range of salinities, it is unlikely that salinity increases will have any directly negative effect on its distribution and abundance. If any direct effect is observed, it will most likely be an increase in abundance on those flats now exposed to suboptimal salinities. Spawning in the clam appears to be temperature regulated, but since diversion should not result in significant temperature changes in the lower estuary, spawning should not be affected.

Changes in patterns of suspended sediment deposition should not affect the distribution and abundance of clams, but if decreased river discharge results in an increased accretion of the flood tidal delta, it is possible that some flats could be partly covered, This, of course, would not happen if dredging prevented sand accumulation.

In the Northeast, the clam is threatened by predation from the green crab, the horseshoe crab, and the moon snail. While none of these predators are presently found on the clam flats, they are living at the mouth of the estuary. Since their distribution and abundance is greatly affected by salinity, it is possible that an increase in salinity could lead to a migration of clam predators onto the flats. Studies dealing with this probability should be explored.

f. Finfish

Even though pollution has seriously reduced the quality of the natural habitat, the Merrimack River Estuary remains rich in diversity and abundance of fishes. Because of the limited amount of data available on life histories of individual species, there is no way of accurately assessing the total impact of a river diversion on all components of the finfish community. However, it is possible to make certain predictions concerning changes that could occur in the ecology of the most abundant species and species of sport and commercial interest.

1) Sand Lance - Because of the intolerance of the sand lance for lowered salinities, it is probable that a reduction in freshwater flow into the estuary could result in a net upriver increase in suitable habitat, and the possibility of an increase in size of the resident population.

2) Striped Bass - The striped bass is equally at home in fresh, brackish, and coastal waters, and in light of the observation that the Merrimack River Estuary is neither a spawning area nor an important over-wintering habitat, diversion of freshwater should have little observeable effect on the ecology or biology of this species.

3) Atlantic Salmon - At present, federal and state fisheries biologists are working to restore natural runs of Atlantic salmon to the Merrimack River. If flow augmentation during low flow periods becomes an important part of such restoration, diversion flows should not intrude on such augmentation plans. Minimum flow limits are extremely important for the success of this restoration program, since both the survival of the smolts in their seaward migration and the success of spawning adults in reaching spawning grounds depend on a sufficient supply of freshwater at specific times throughout the year. In view of this, any diversion plan should consider the salmon restoration program, and the flows necessary to ensure its success.

4) Shad - As in the case of the salmon restoration program, success in shad restoration depends on the presence of minimum flows at certain times of the year, particularly when adults are returning to the spawning grounds and juveniles are migrating to the seas. In addition, success in both restoration programs will only come after additional problems, such as pollution abatement and construction of effective fish ladders, are resolved.

5) Alewife and Herring - It is probable that alewife and herring runs will become re-established on the Merrimack River when suitable fish ladders are constructed. As is the case for the shad and salmon, minimum flows are essential for successful re-establishment of the species.

6) Atlantic Mackerel - Mackerel is an open ocean fish, even though it often feeds inshore. Since diversion should have no effect on any important prey species, no effect on the mackerel population should be seen.

7) Winter Flounder - The winter flounder spawns over a wide range of salinities, and is considered to be euryhaline throughout its life, but shows a preference for estuarine waters at certain ages. A periodic increase in salinity in the estuary should not greatly affect the ecology of the species, but its metabolic requirements should be considered further.

8) American Eel - The American eel is extremely tolerant to both salinity and temperature variation, and considering the wide variety of their diet, there is no reason to believe that diversion of freshwater from the Merrimack River would have any effect on its distribution and abundance.

4. <u>Potential Effects of Diversion on the Parker River Estuary and the Parker River National Wildlife Refuge</u>:

Studies indicate that even though waters of the Parker River Estuary and the Merrimack River Estuary are connected, there apparently is little net exchange between the two systems. Because of this, there is no evidence to indicate that changes in salinity in the Merrimack River Estuary will affect the Parker River Estuary and the Parker River National Wildlife Refuge in any manner.

B. CONCLUSIONS

Because of the complexity of an ecosystem, simplistic answers relating to effects of physical changes are usually not possible. The reliability of predicting ecological effects resulting from alterations of the physical environment is generally dependent upon the magnitude of the proposed change.

A review of the proposed diversion schemes, as outlined in Sections I, III, and IV of this report, indicates that certain diversion rates would probably have no detectable effects on the ecology of the Merrimack River Estuary. However, other diversion rates may produce effects. These could be either desirable or undesirable. It is not possible, however, to make definite predictions on the magnitude of these effects, but only to describe them as significant or insignificant.

Several important criteria have emerged in the evaluations of possible ecological effects on diversion. These are based essentially on present normal fluctuations of various environmental conditions occurring within the estuary and include normal periods of salinity stratification and mixing; normal salinity distribution within the length of the estuary; minimum flows which occur within the estuary; and normal variations in temperature, dissolved oxygen, and sediment rates.

By incorporating the suggested diversion rates and control flows proposed in the scope of work outlined in the project description, and reviewing the historic record of flows for the period 1927-1967, the projected changes in salinity distribution generated by the mathematical model, the results of biological field investigations, literature research, and consultation with various organizations and agency personnel, the following evaluations have been made.

In our best judgement, at diversion rates of

100 cfs	No significant ecological effects are predicted for any month of the year.
300 cfs	It is unlikely that any significant ecological effects would occur during any month of the year.
500 cfs - 800 cfs	No significant ecological effects are predicted for the months of January, February, March, April, May, June, November, or December. However, during

	the months of July, August, September, and October, the prediction is made that effects are possible, but there is insufficient data to speculate on their magnitude.
1,100 to 2,000 cfs	July, August, September, and October - Significant ecological effects are probable.
	January, February, June, November, and December - Effects are possible but cannot be predicted.
	March, April, and May - No effects are expected.

The proposal to provide upstream storage during high flow, and flow augmentation during low flow periods, has also been evaluated for possible ecological effects. A review of the proposed diversion rates, ranging from 185 cfs to 8,050 cfs, indicates that effects may be expected during spring when water is being stored. While the magnitude of ecological effects during spring storage is unknown, it should be emphasized that these flows are essential in maintaining the ecological balance of any river or estuary. This is particularly true for anadromous fishes. During periods of low discharge, flows would be augmented to maintain desired diversion rates without exceeding control levels, and thus the estuary should not experience any change. Additional studies incorporating proposed retention rates and discharge schedules should be conducted if this plan is implemented.

Although no additional effects are postulated for the Merrimack

River Estuary other than those relating to the net reduction in flows as discussed in the previous section, higher flows experienced above the point of diversion resulting from augmentation may produce significant effects and should be considered in the future.

C. RECOMMENDATIONS

It is recommended, based on the data collected and the results summarized in this section, that as a part of the proposed diversion a carefully developed ecological monitoring program be implemented. This should consist of both pre- and post-operational monitoring. Operation of the diversion system should be keyed to the result of this monitoring. In addition, it is recommended that studies on possible ecological effects of diversion be continued to further refine the present predictions. Areas of study should include a survey to determine the exact flow rates at which salinity destratification occurs within the estuary and river. More detailed studies should be conducted of possible effects of proposed diversion rates on sediment deposition and sand movement, changes in water temperature, and possible intrusion or upstream movement of predators.

Since diversion systems are by their design controllable, operation of the system should be regulated so effects on the estuary remain minimal. It is suggested, therefore, that operation should be coordinated with information derived from the ecological monitoring program.

ECOLOGICAL STUDY

MERRIMACK RIVER ESTUARY - MASSACHUSETTS

VIII. LITERATURE CITED

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*Indicates reference used but not cited in report.

APPENDICES

APPENDIX A

HIGH TIDE SALINITY DISTRIBUTIONS

REFERENCE

SALINITY STUDY, MERRIMACK RIVER ESTUARY
MATHEMATICAL STUDY

DIVERSION INDEX

DIVERSION / FLOW	(Cubic Feet per Second)													
	100	200	300	500	600	800	1000	1100	1500	1900	2000	2800	5200	8000
800														
850														
900														
950	2													
1000	3							1*						
1100	5	3												
1200	6	5	3											
1300	7	6	5											
1400	8	7	6	3										
1500	9	8	7	5	3									
1600	10	9	8	6	5									
1700	11	10	9	7	6	3								
1800	12	11	10	8	7	5								
1900	13	12	11	9	8	6	3							
2000	14	13	12	10	9	7	5	3						
3000	16	16	16	15	15	15	15	15	10	5	5			
4000	17	17	17	17	16	16	16	16	15	15	15	7		
5000	18	18	18	17	17	17	17	17	17	16	16	15		
6000	19	19	19	19	18	18	18	18	17	17	17	16		
7000	20	20	20	19	19	19	19	19	19	18	18	17	13	
8000	21	21	21	21	20	20	20	20	19	19	19	18	16	
10000	22	22	22	22	22	22	21	21	21	21	21	20	18	15
12000	23	23	23	23	23	23	22	22	22	22	22	22	20	17
14000	24	24	24	24	24	24	24	23	23	23	23	23	21	19
16000	25	25	25	25	25	25	25	24	24	24	24	24	22	21
cfs														

*All blank table entries refer to Figure 1 of Appendices A and B for high and low tides, respectively. Figures 1 (A & B) represent the minimum control flow established by the Corps of Engineers.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 800. CFS

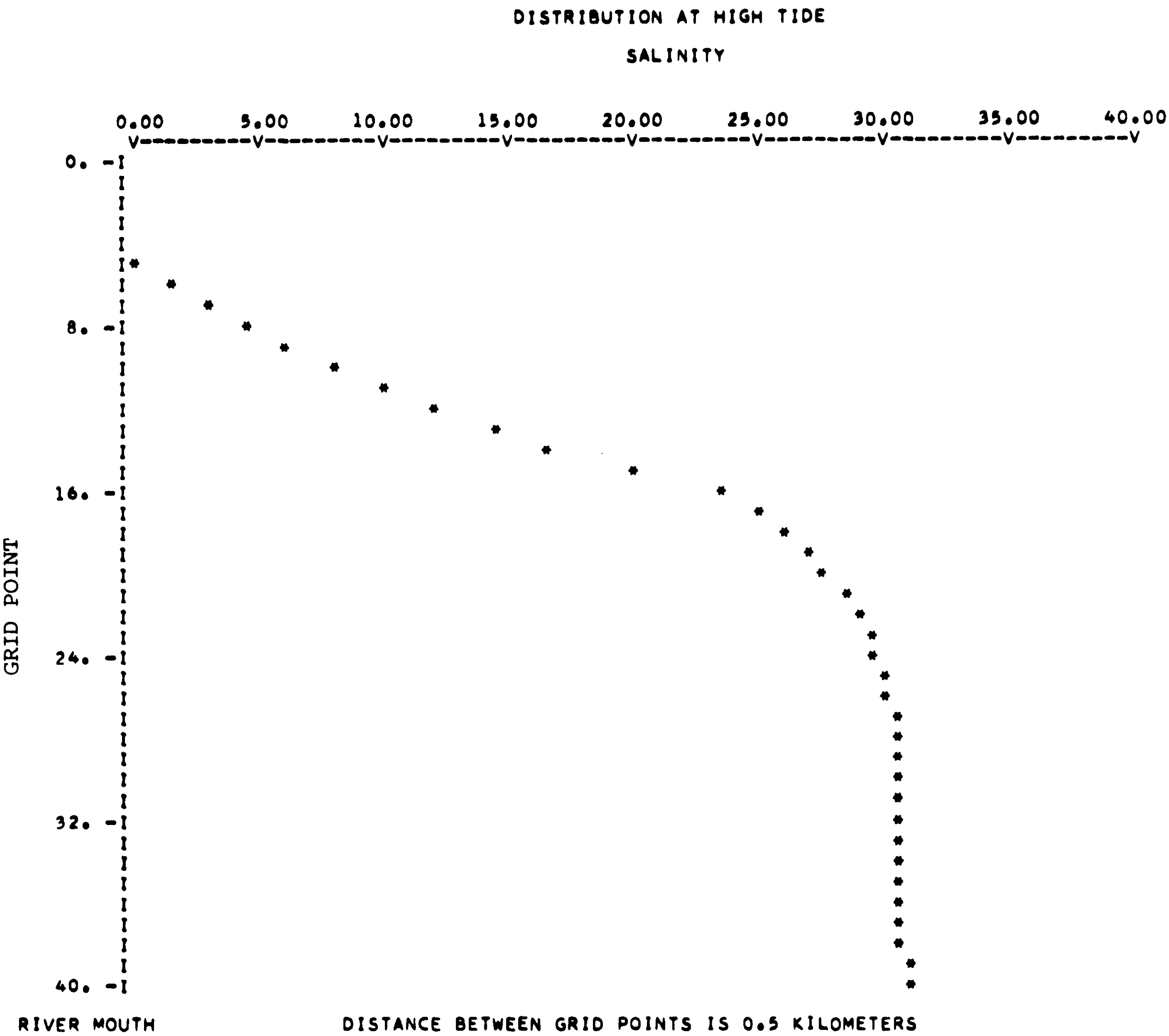


FIGURE A-1.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 850. CFS

DISTRIBUTION AT HIGH TIDE

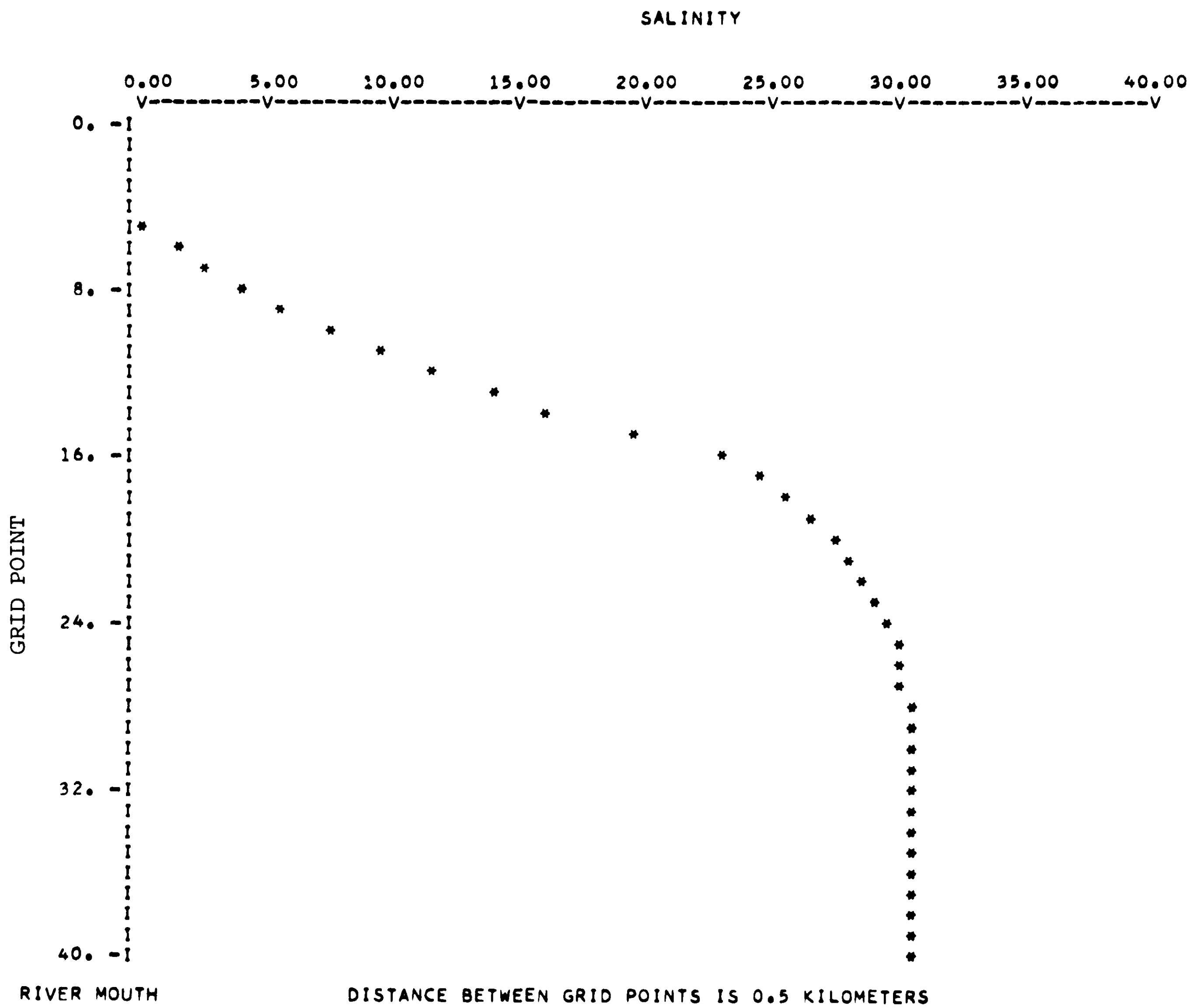


FIGURE A-2.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 900. CFS

DISTRIBUTION AT HIGH TIDE

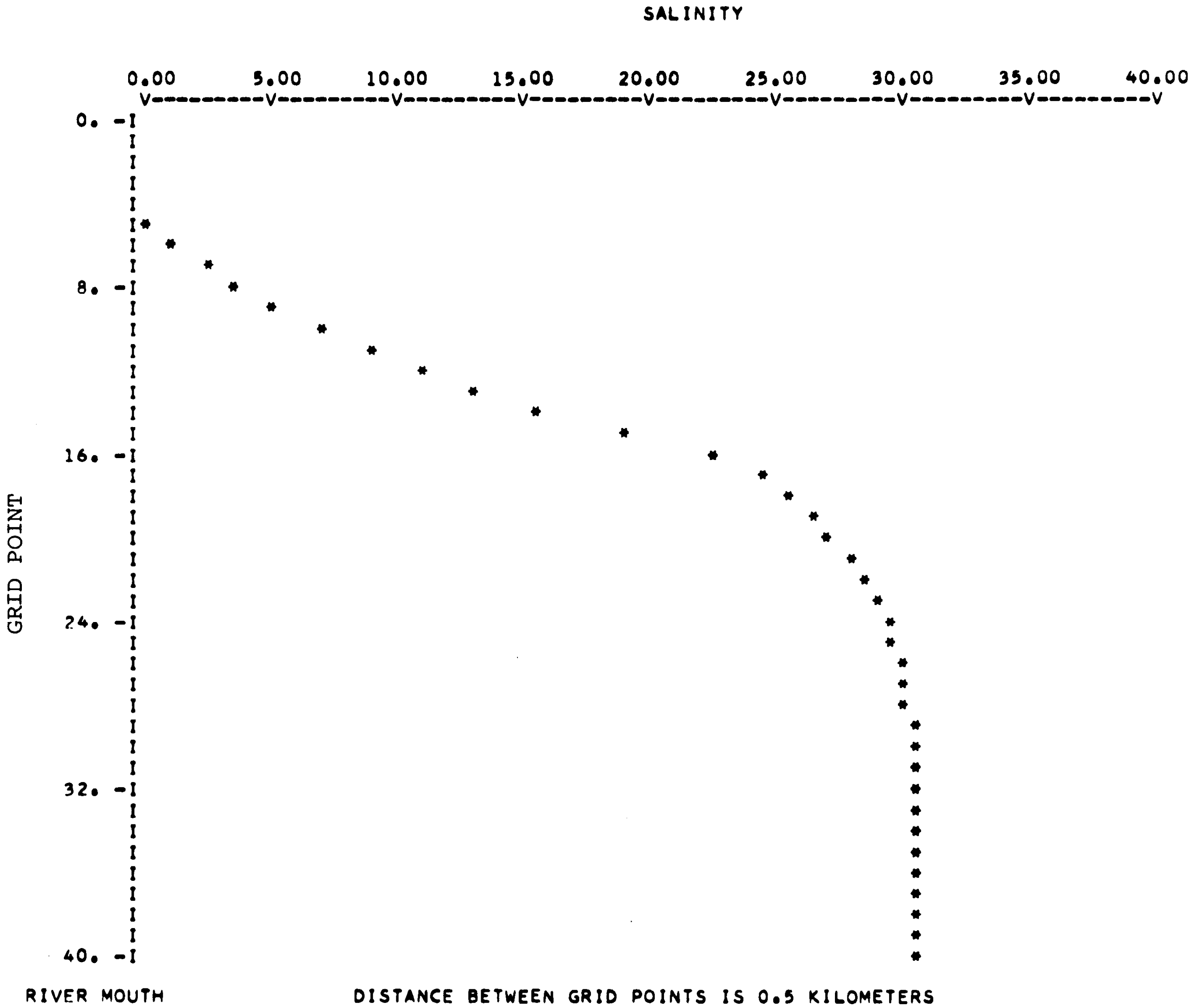
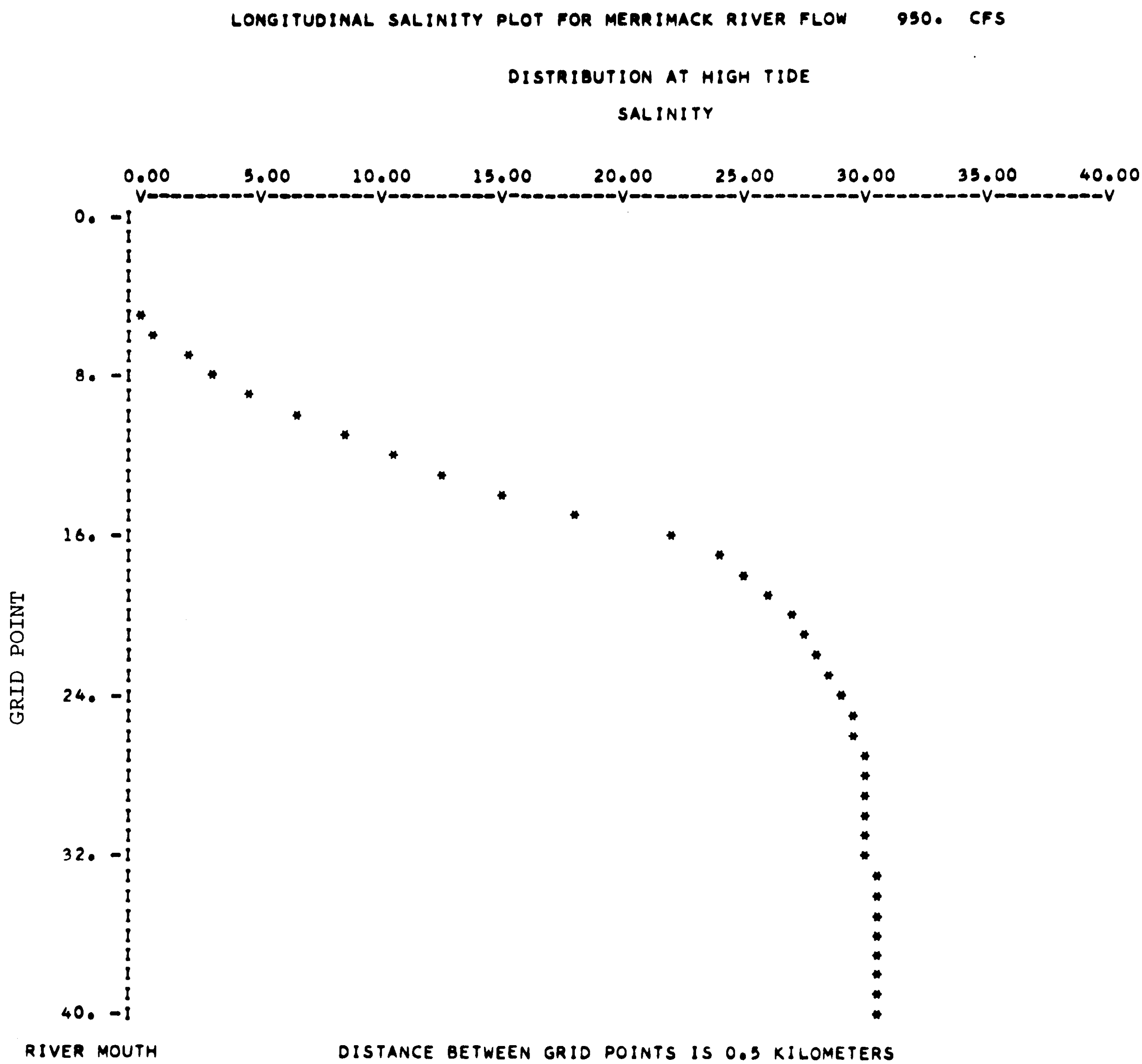


FIGURE A-3.



LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 950. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-4.

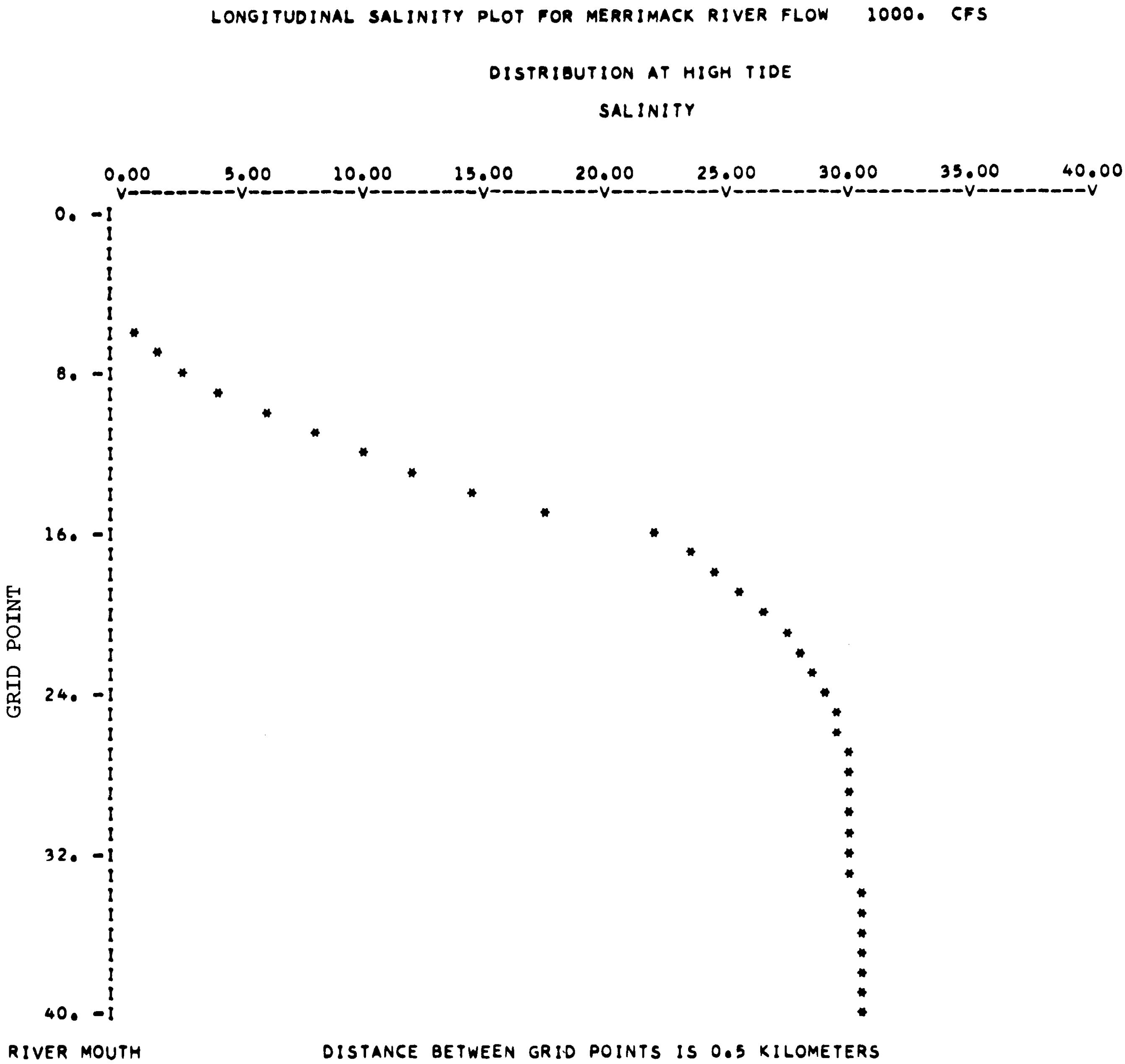

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1000. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-5.

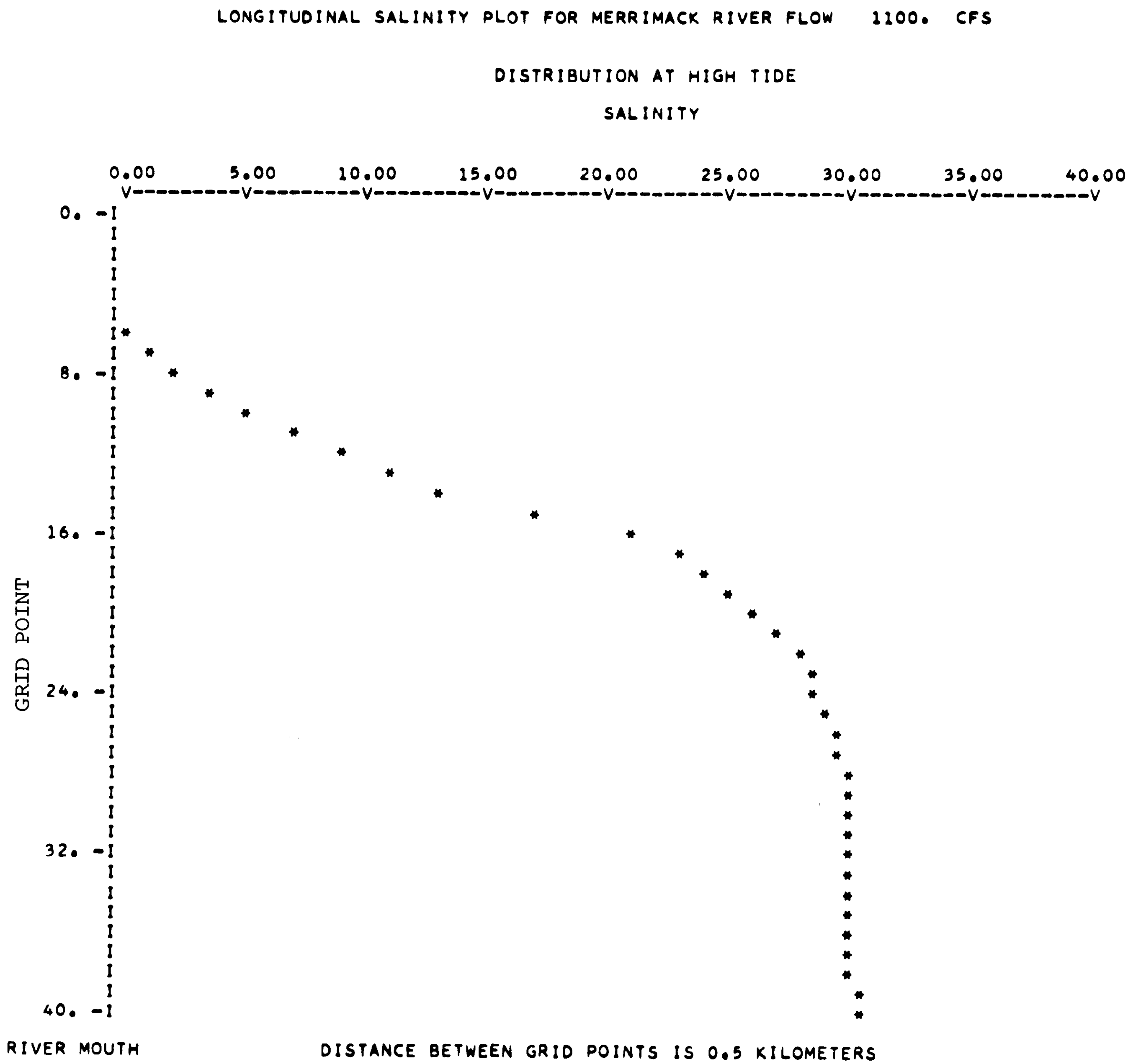

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1100. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-6.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1200. CFS

DISTRIBUTION AT HIGH TIDE

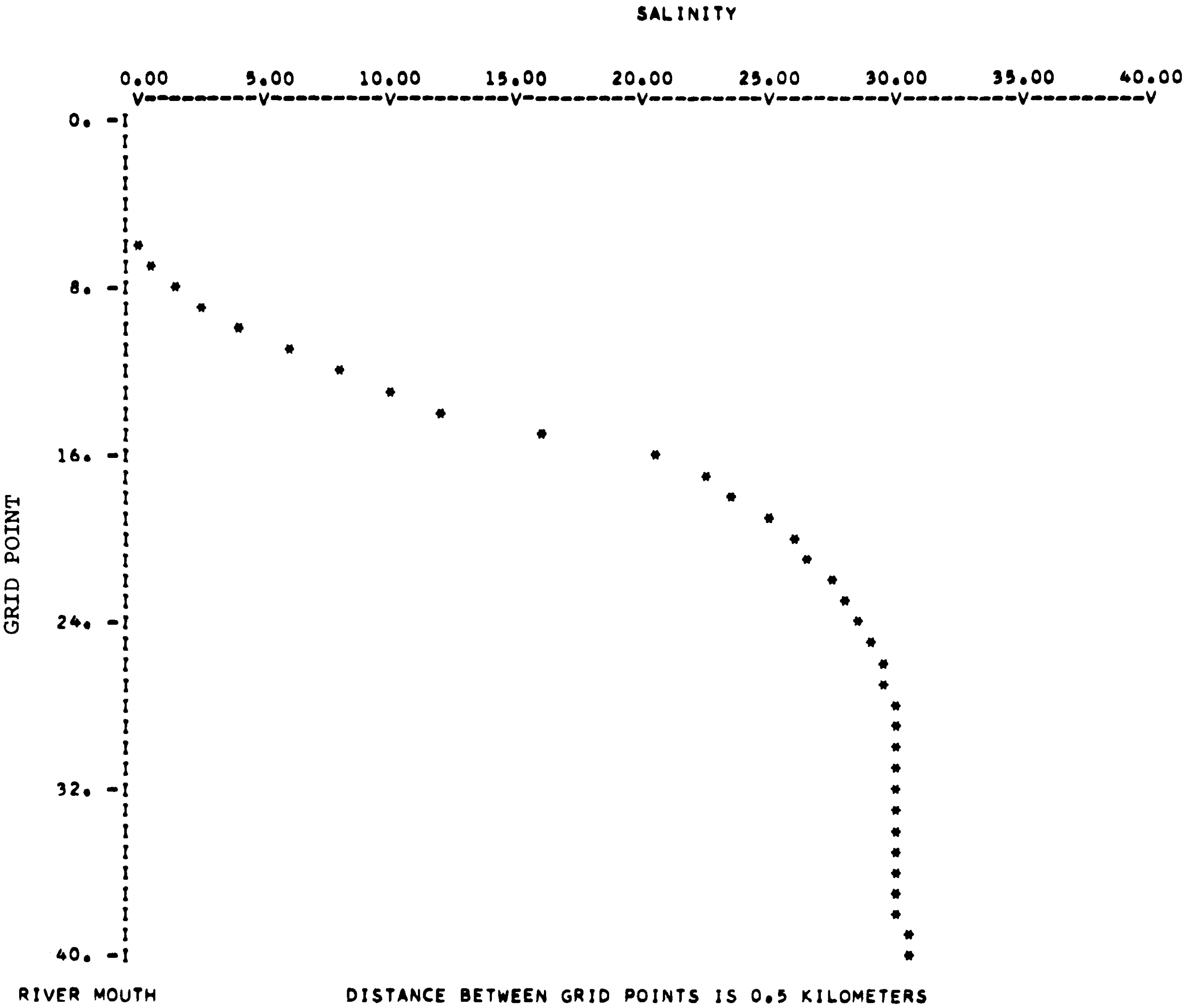


FIGURE A-7.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1300. CFS

DISTRIBUTION AT HIGH TIDE

SALINITY

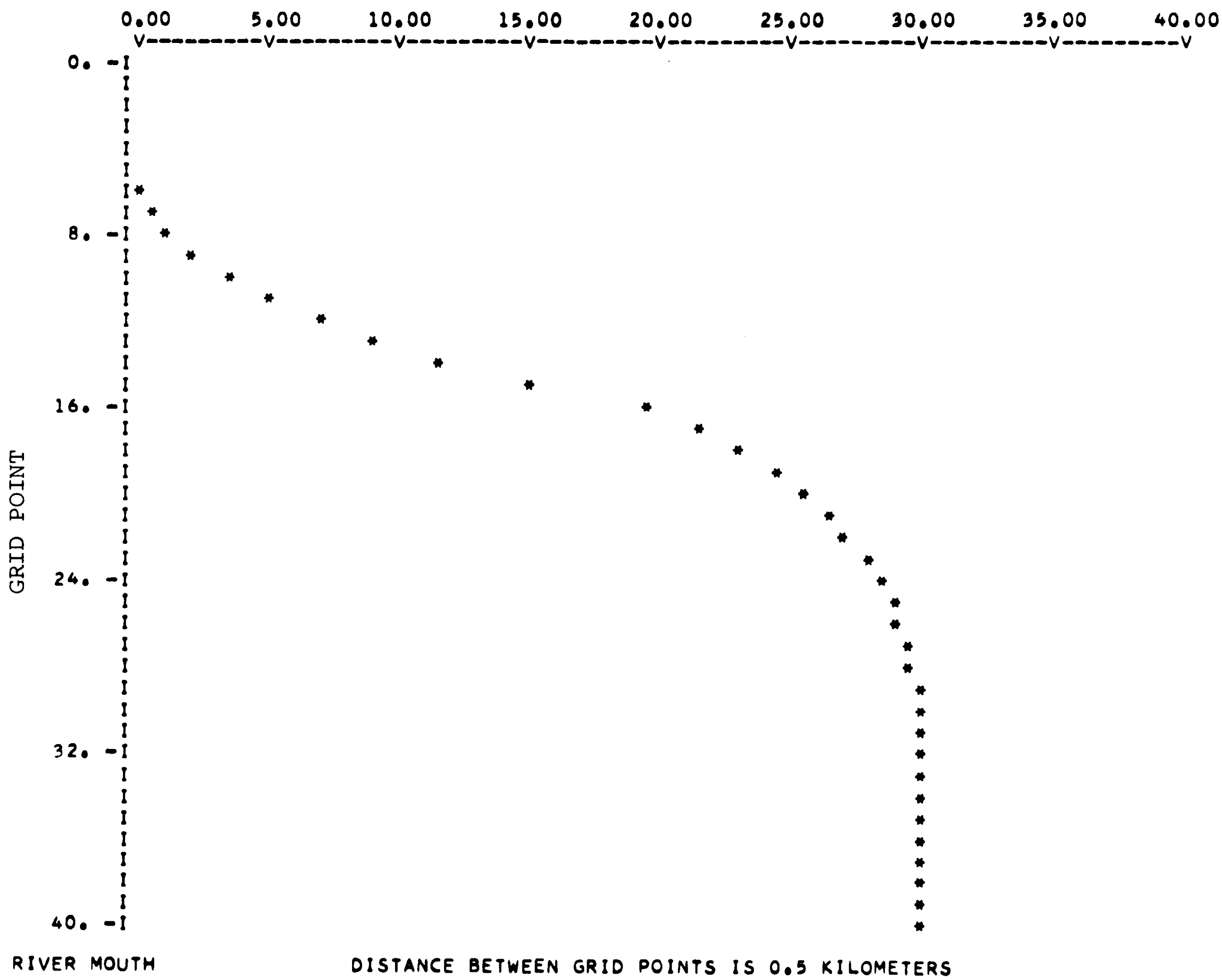


FIGURE A-8.

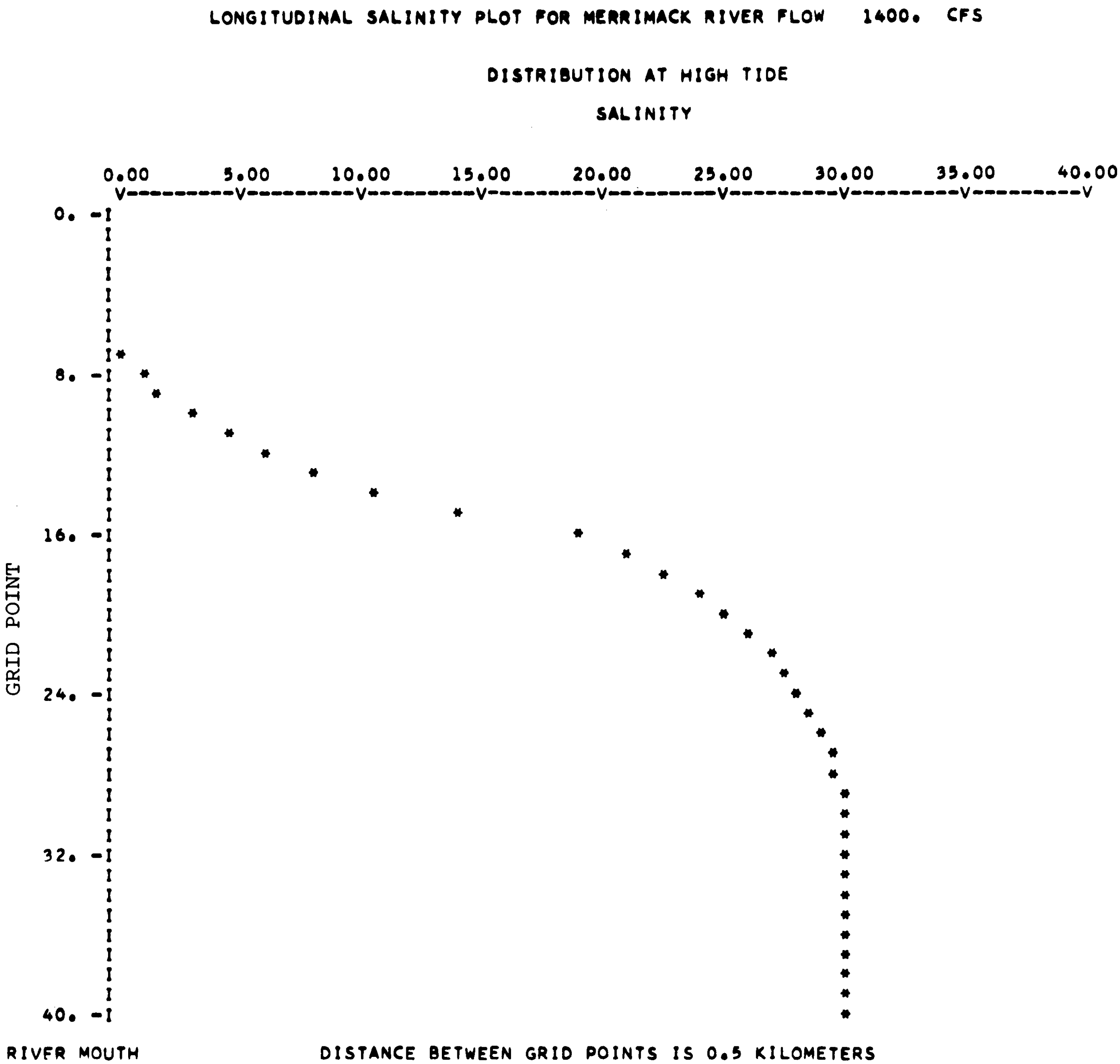

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1400. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-9.

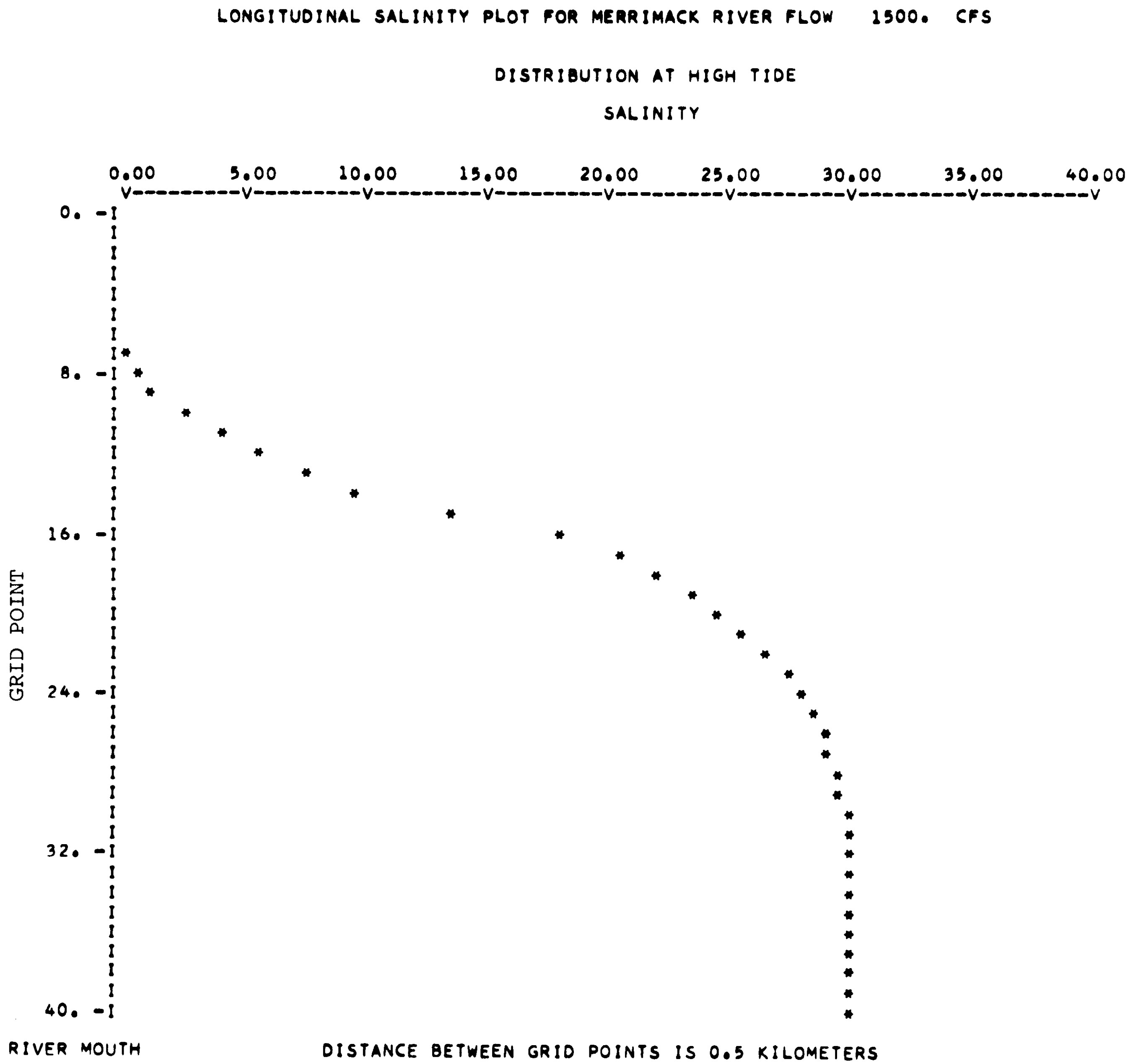

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1500. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-10.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1600. CFS

DISTRIBUTION AT HIGH TIDE

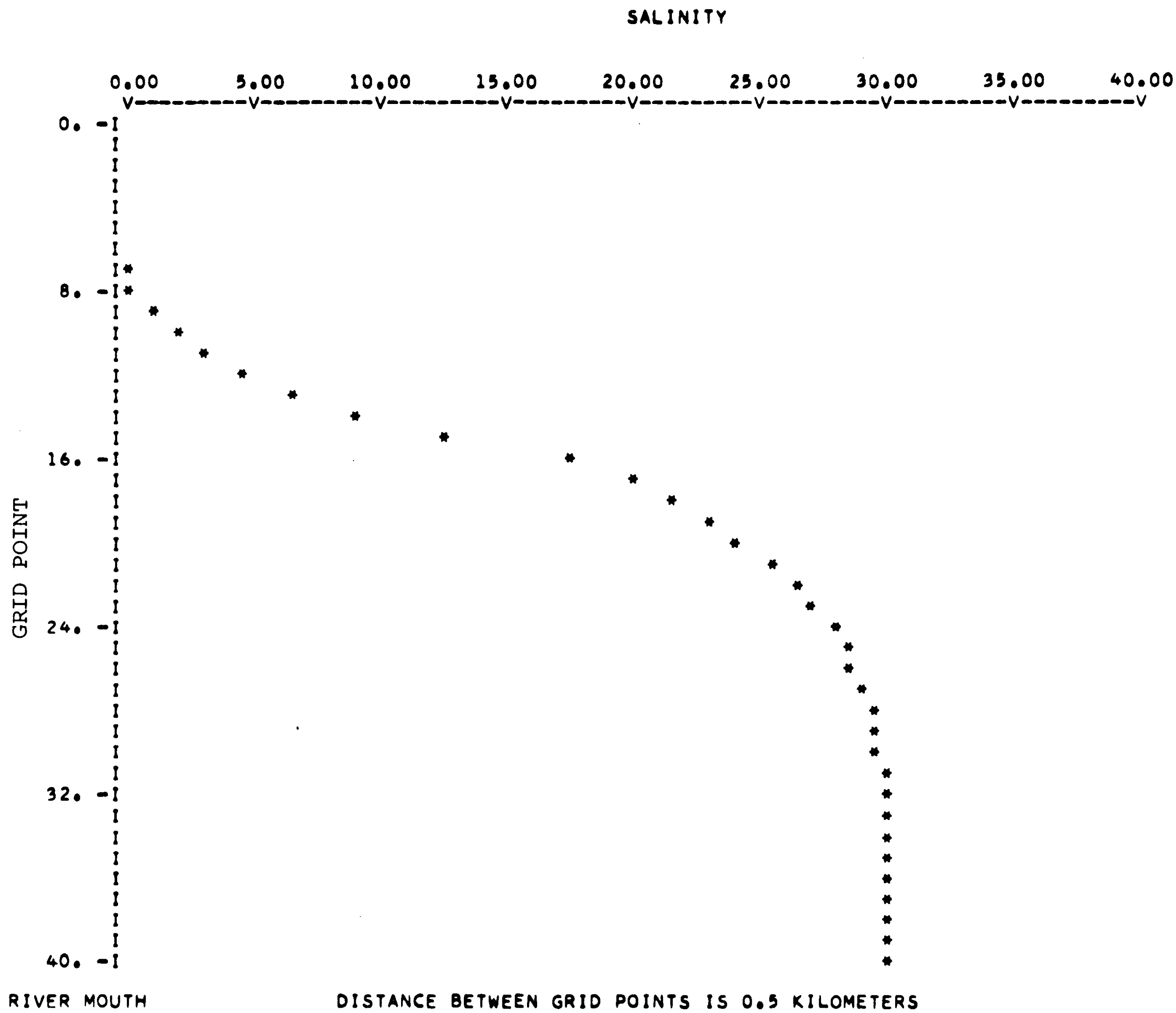


FIGURE A-11.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1700. CFS

DISTRIBUTION AT HIGH TIDE

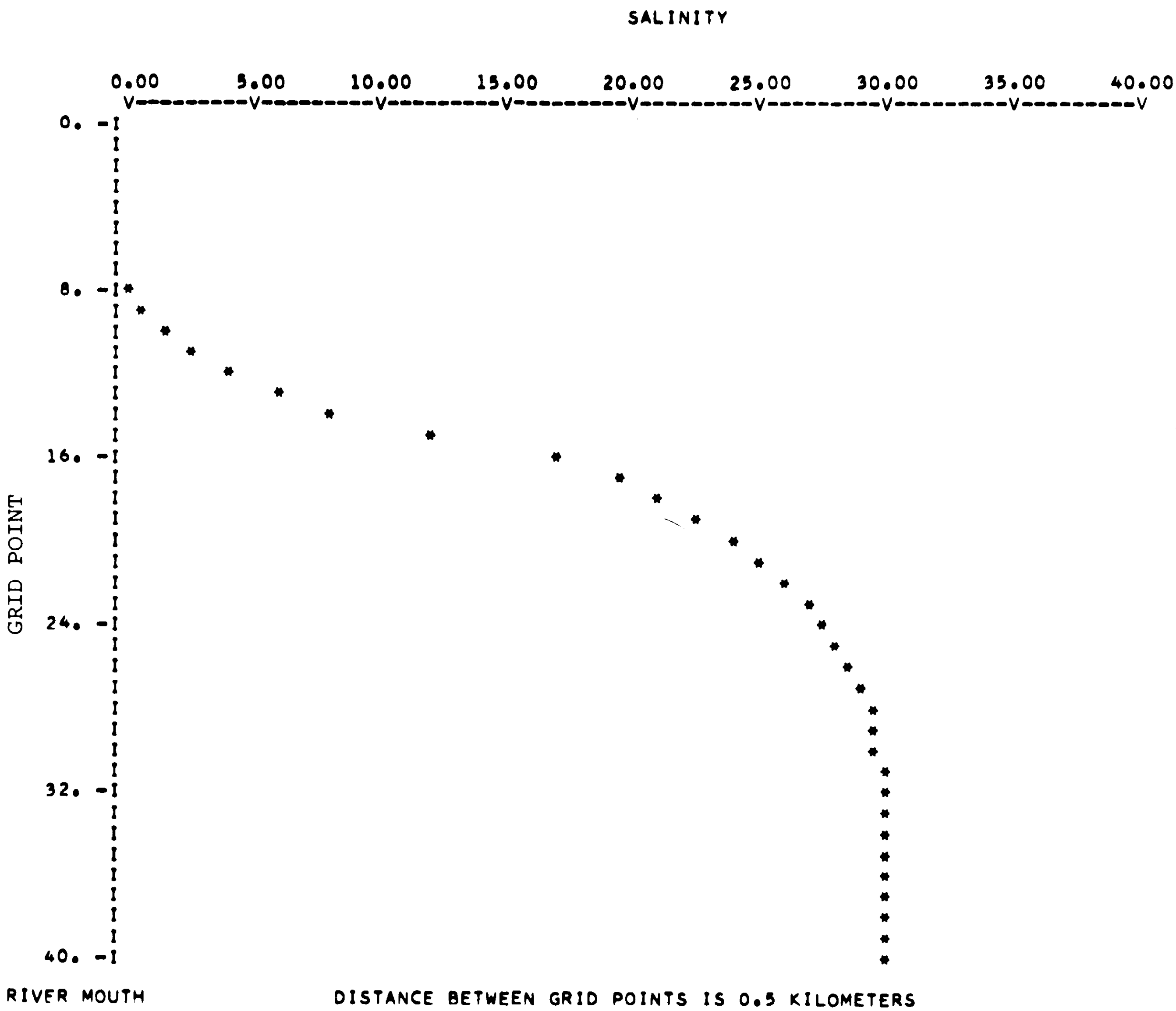


FIGURE A-12.

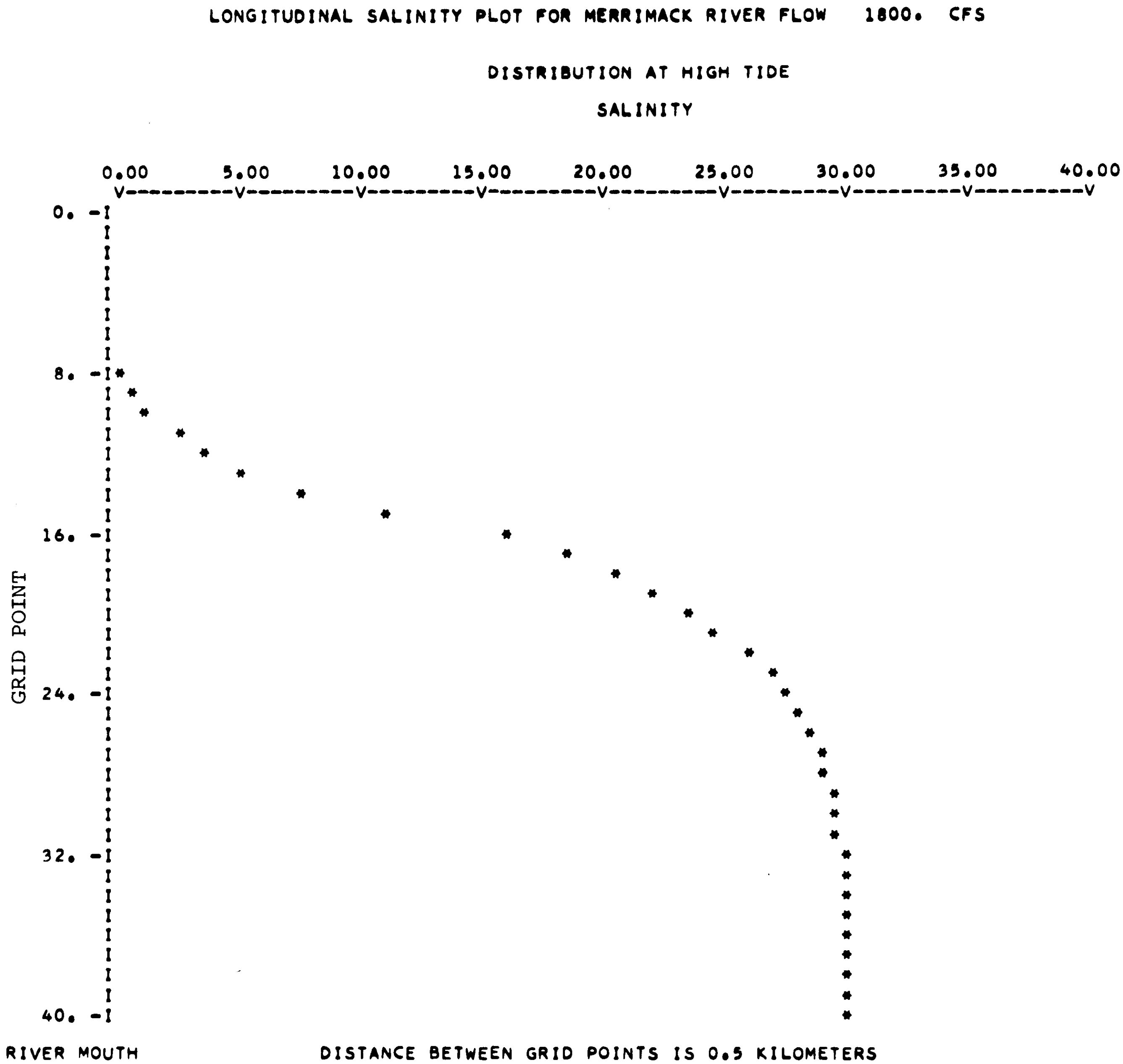

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1800. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-13.

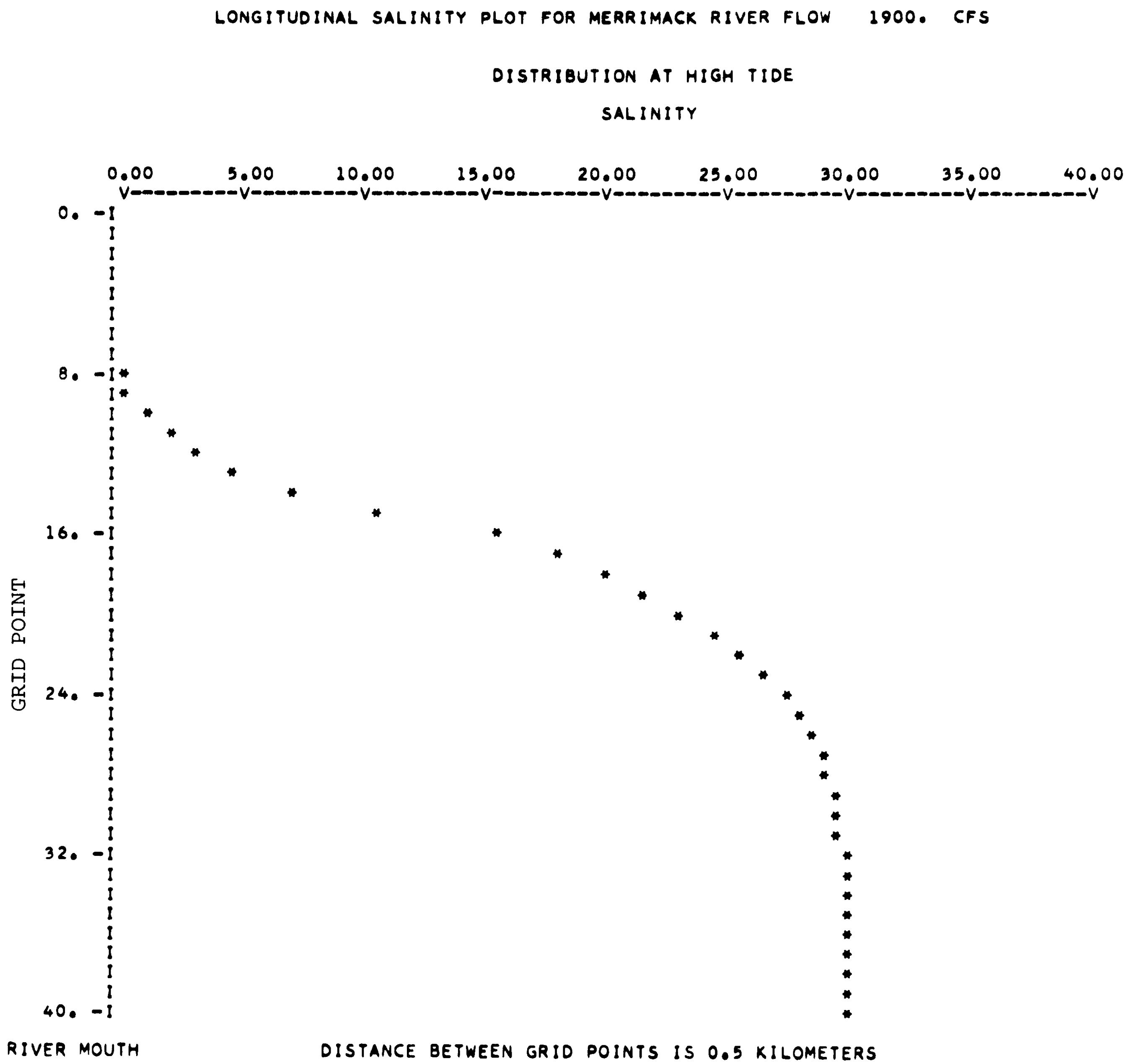

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1900. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-14.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 2000. CFS

DISTRIBUTION AT HIGH TIDE

SALINITY

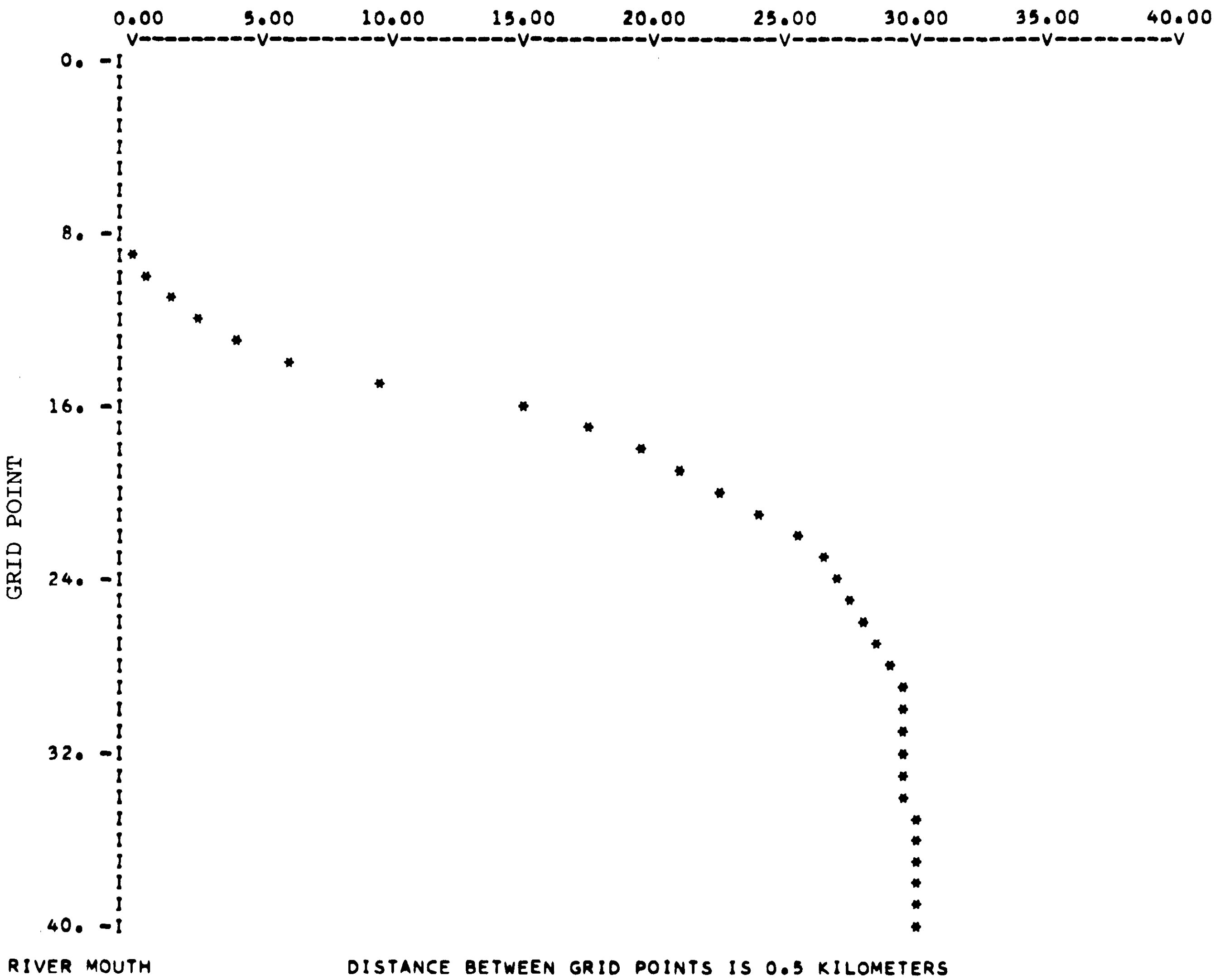


FIGURE A-15.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 3000. CFS

DISTRIBUTION AT HIGH TIDE

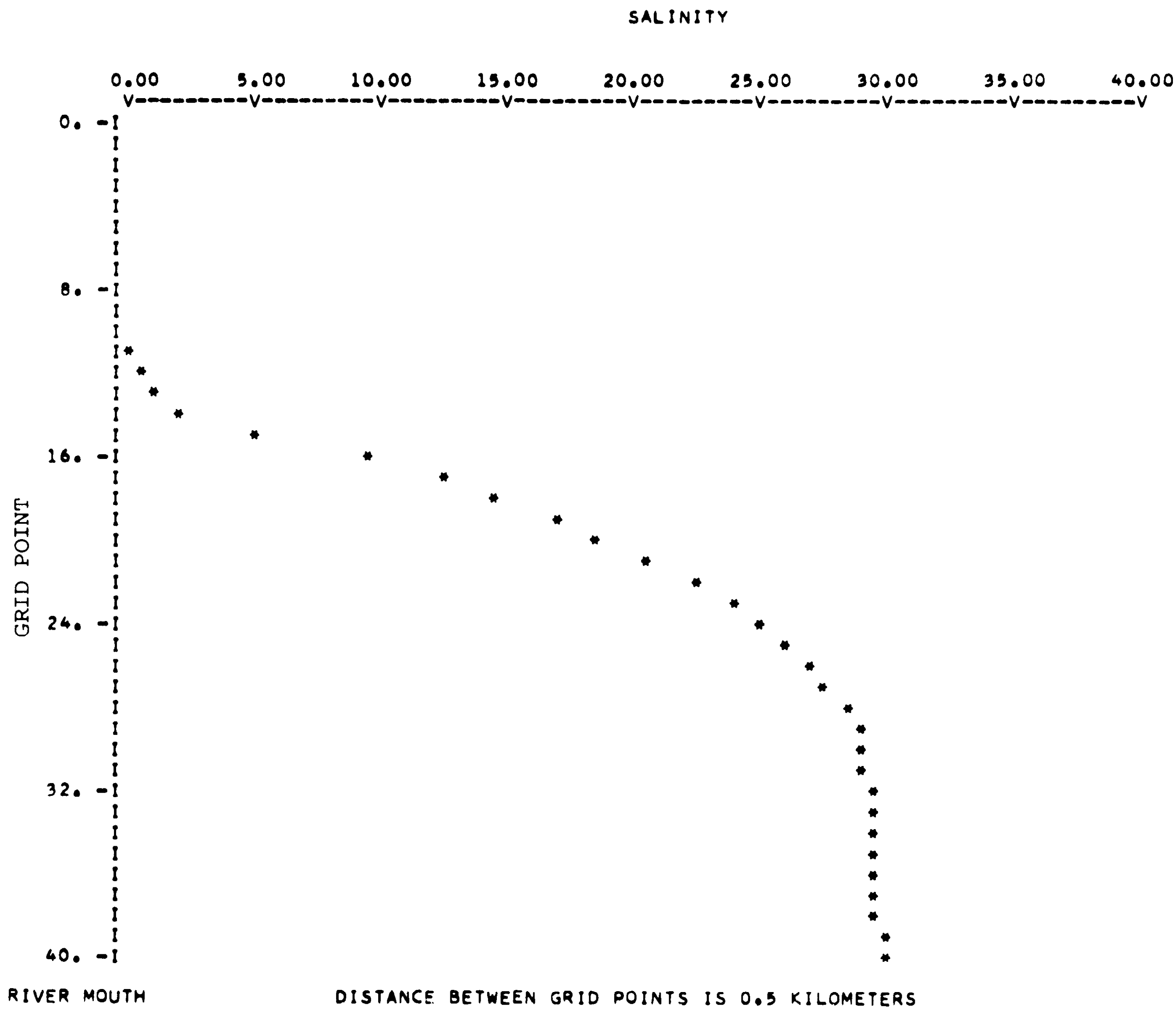


FIGURE A-16.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 4000. CFS

DISTRIBUTION AT HIGH TIDE

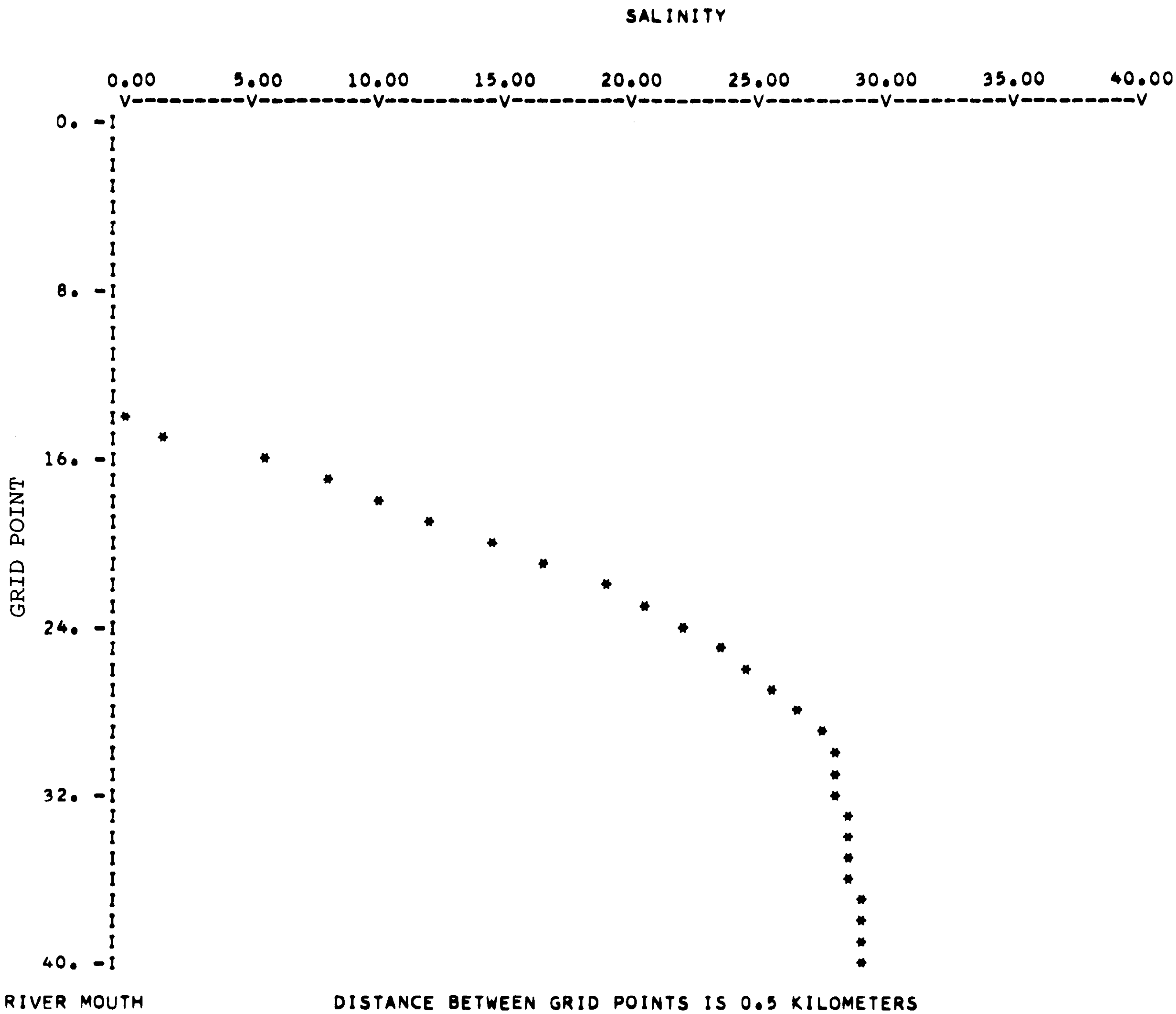


FIGURE A-17.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 5000. CFS

DISTRIBUTION AT HIGH TIDE

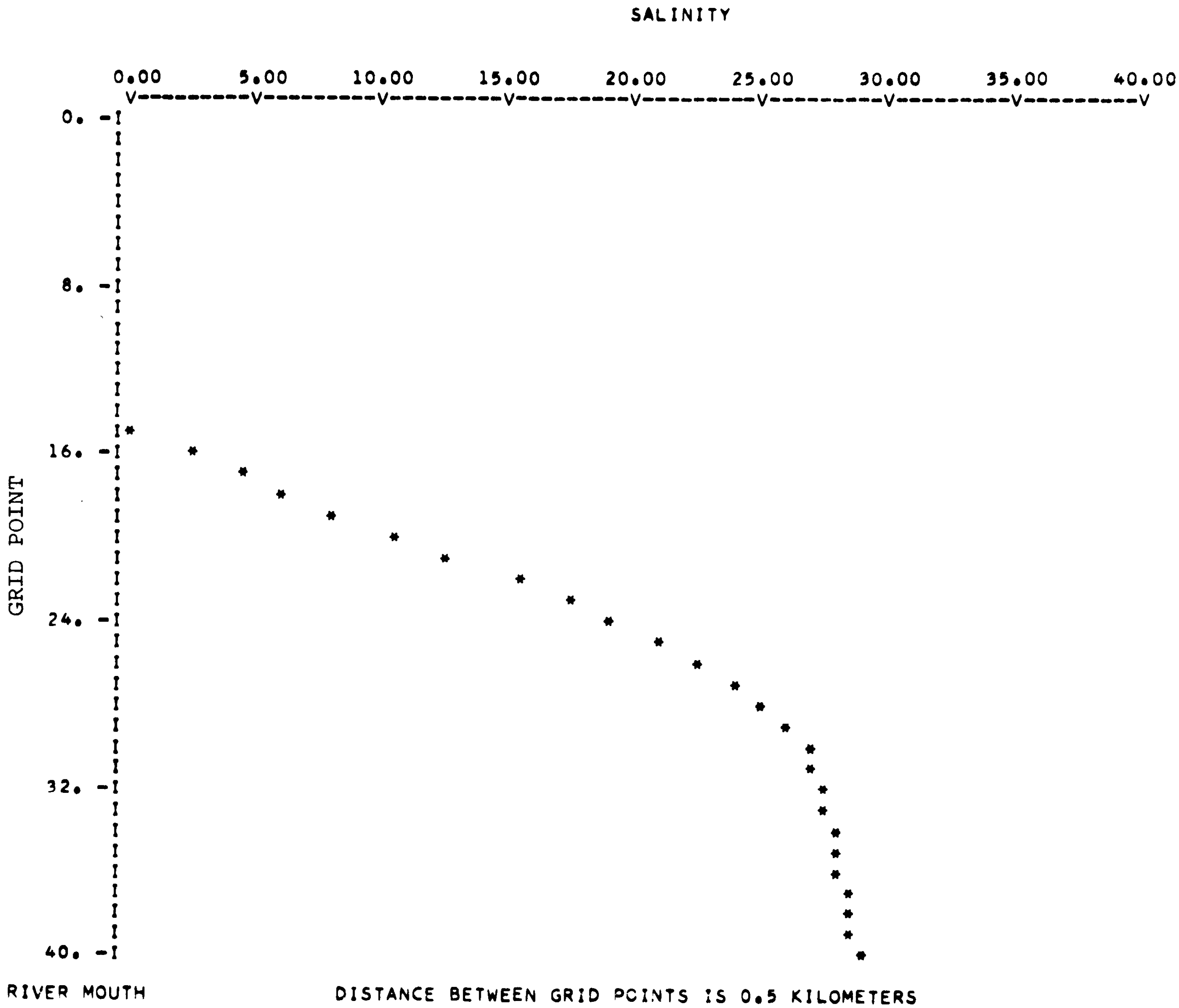


FIGURE A-18.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 6000. CFS

DISTRIBUTION AT HIGH TIDE

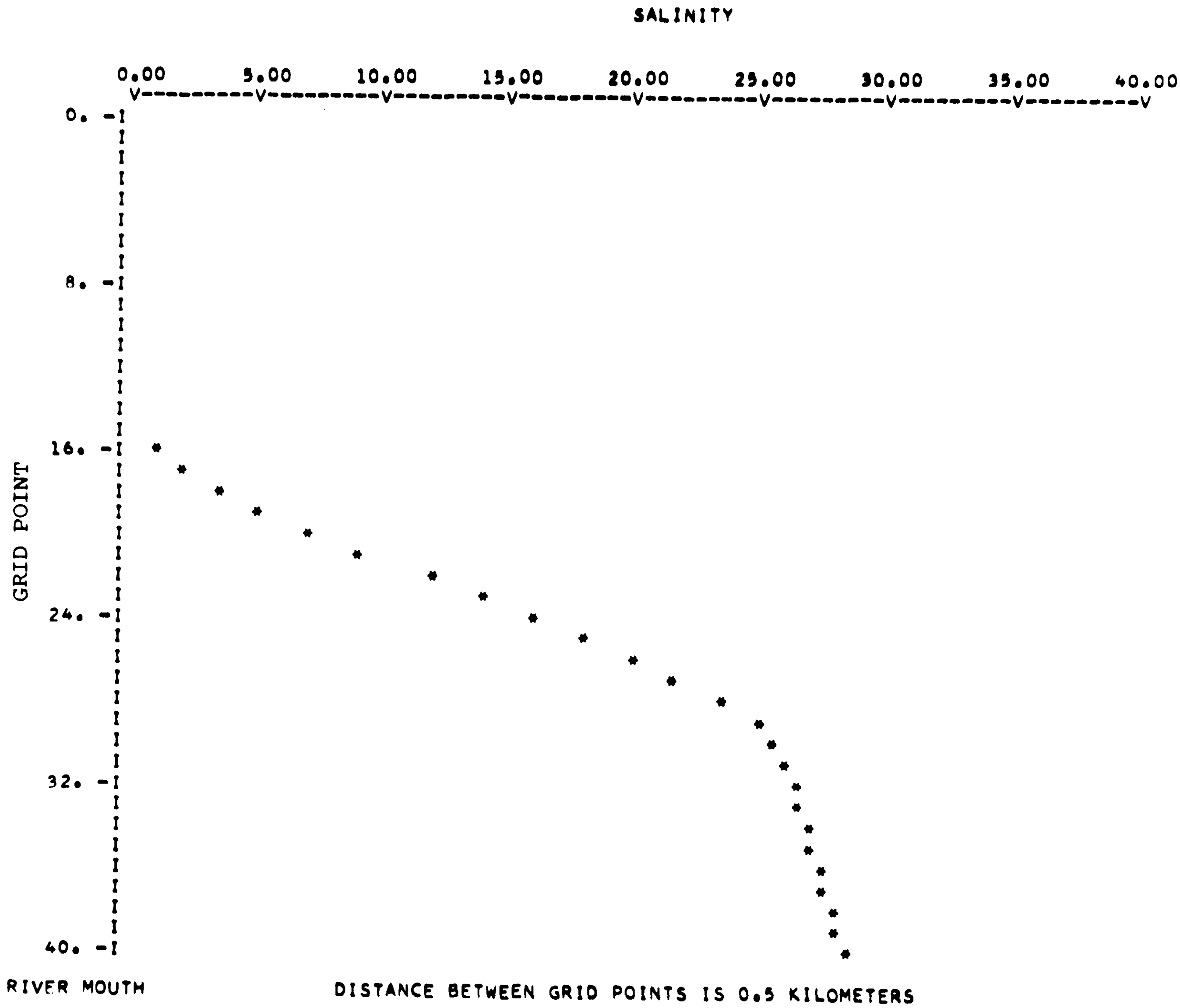
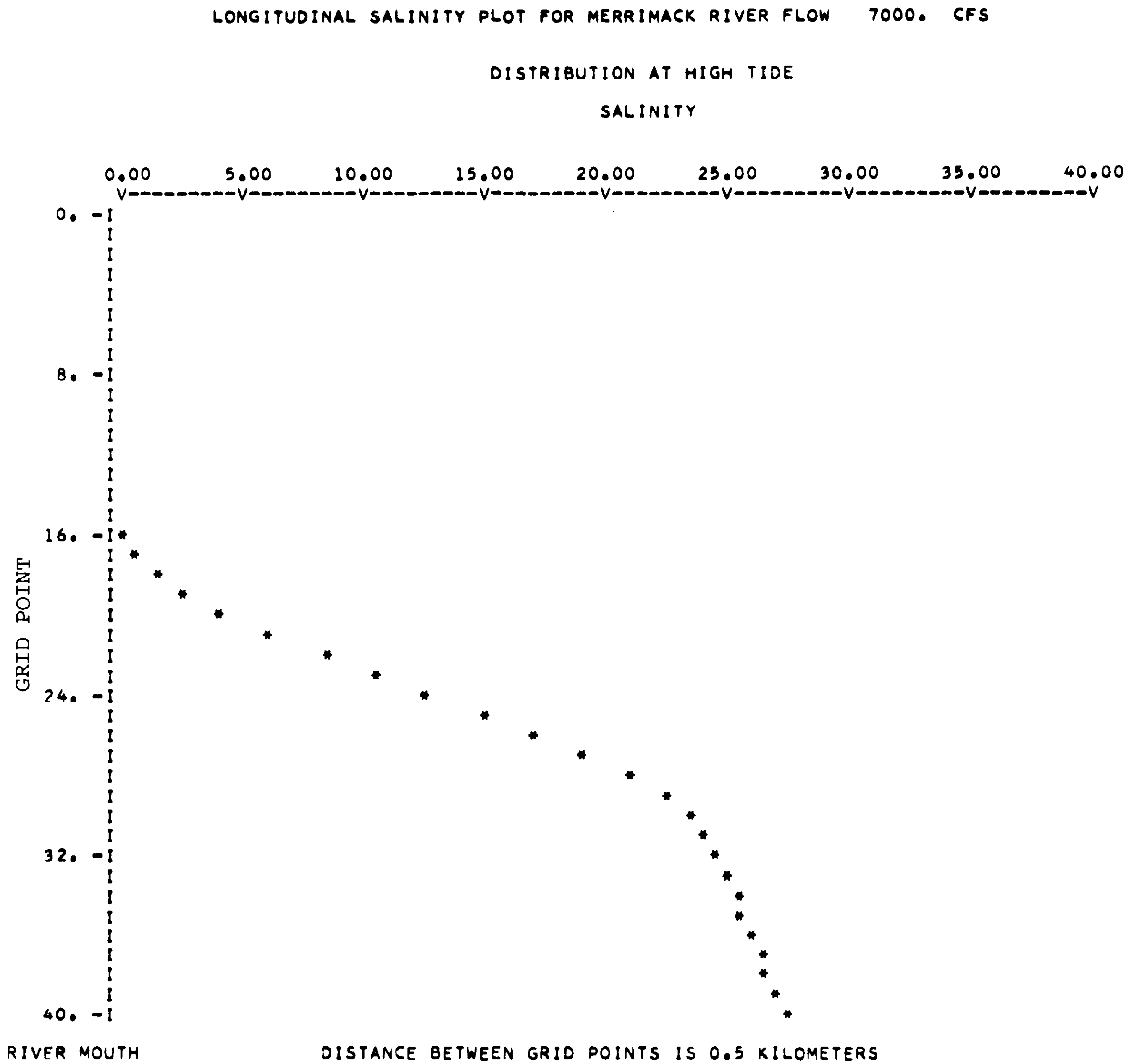


FIGURE A-19.



LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 7000. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-20.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 8000. CFS

DISTRIBUTION AT HIGH TIDE

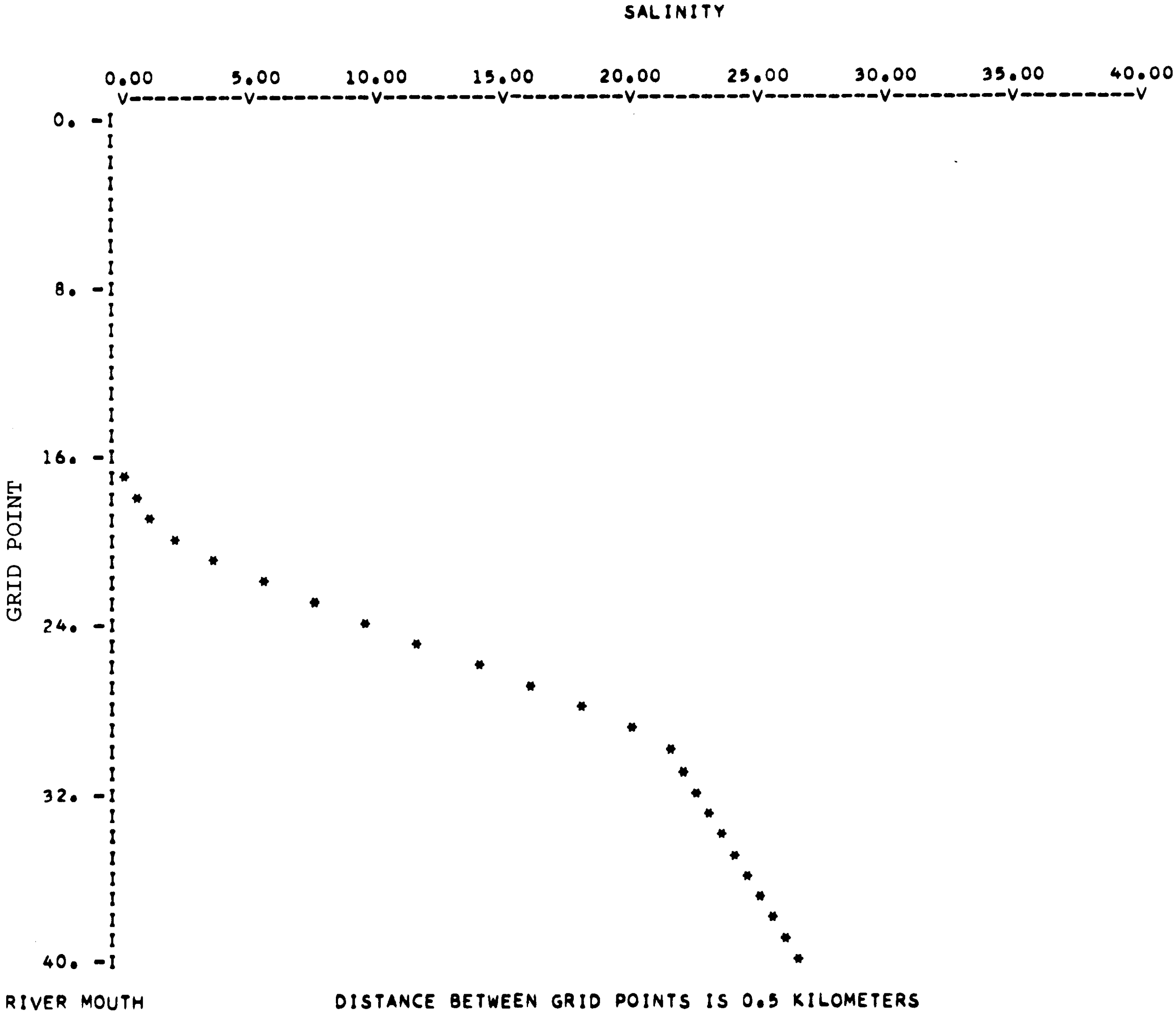


FIGURE A-21.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 10000. CFS

DISTRIBUTION AT HIGH TIDE

SALINITY

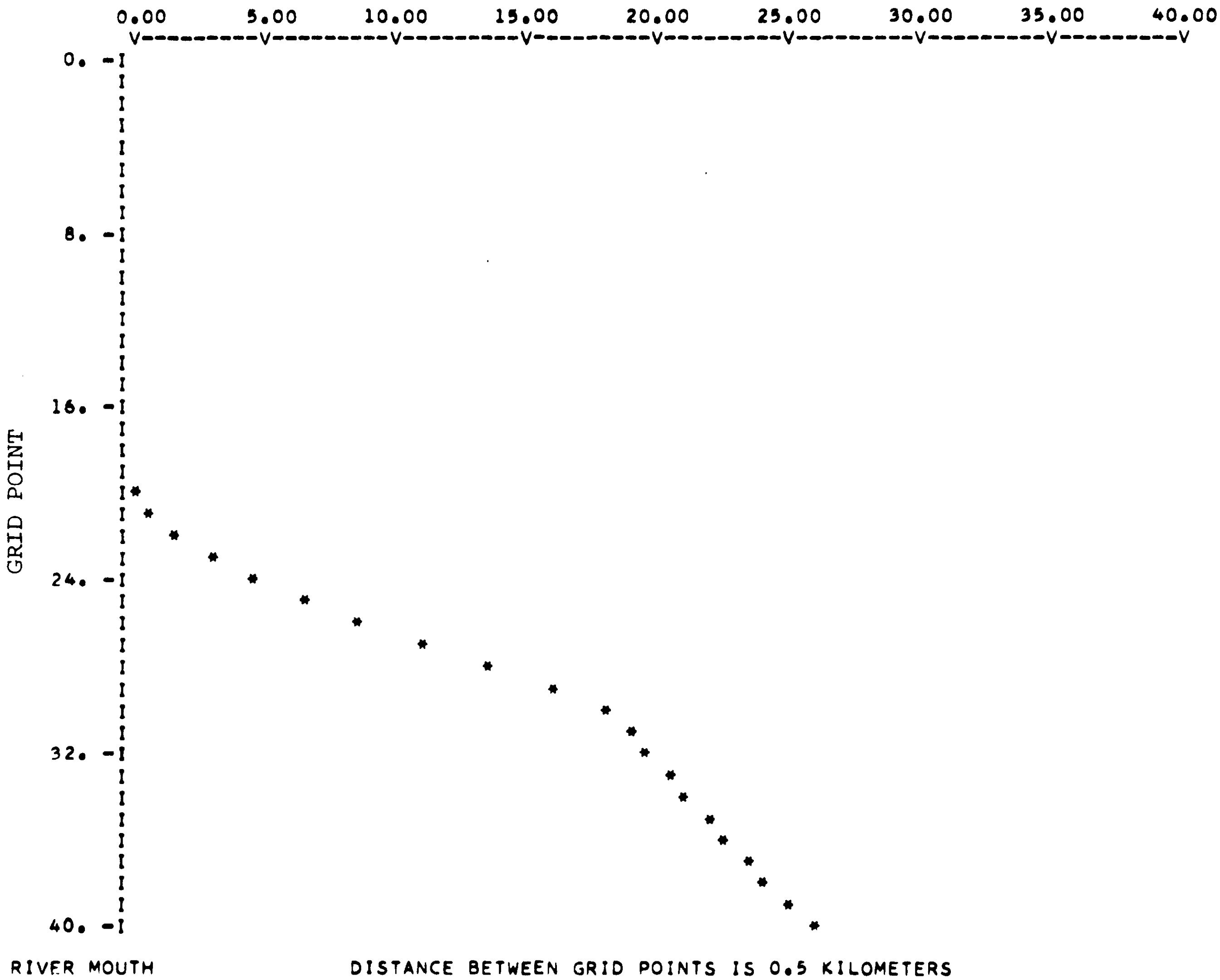
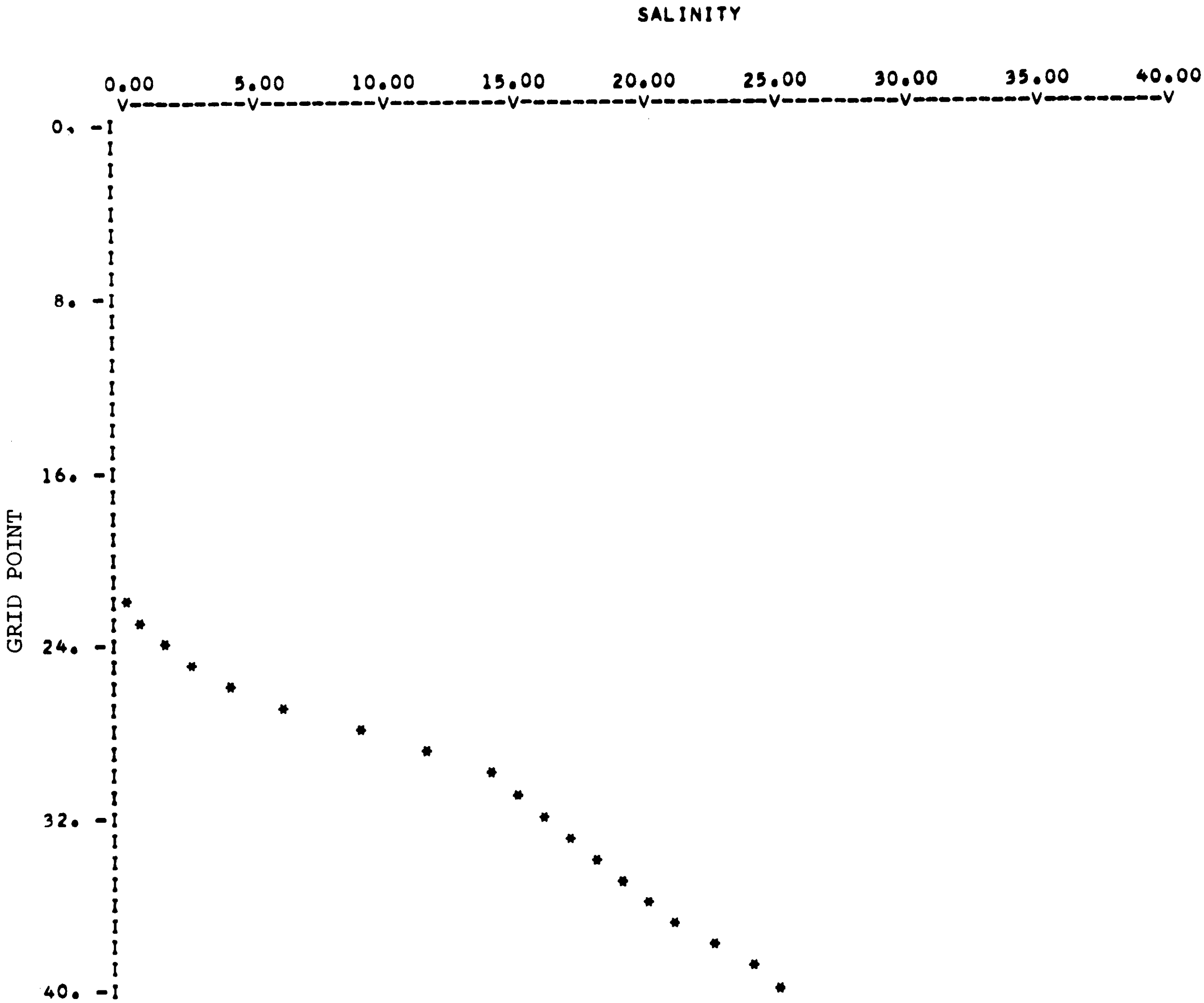


FIGURE A-22.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 12000. CFS

DISTRIBUTION AT HIGH TIDE



DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-23.

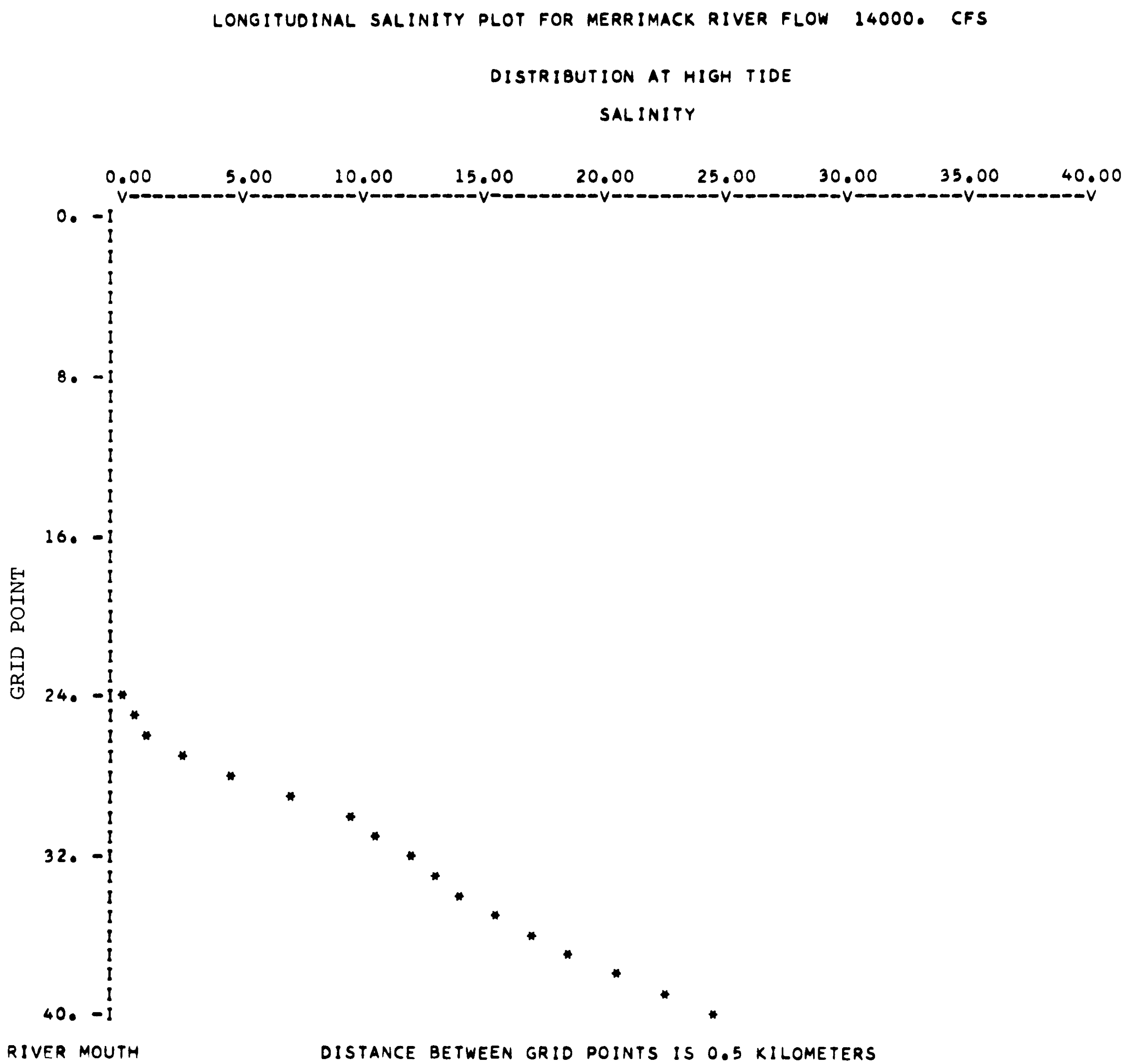

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 14000. CFS
DISTRIBUTION AT HIGH TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE A-24.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 16000. CFS

DISTRIBUTION AT HIGH TIDE

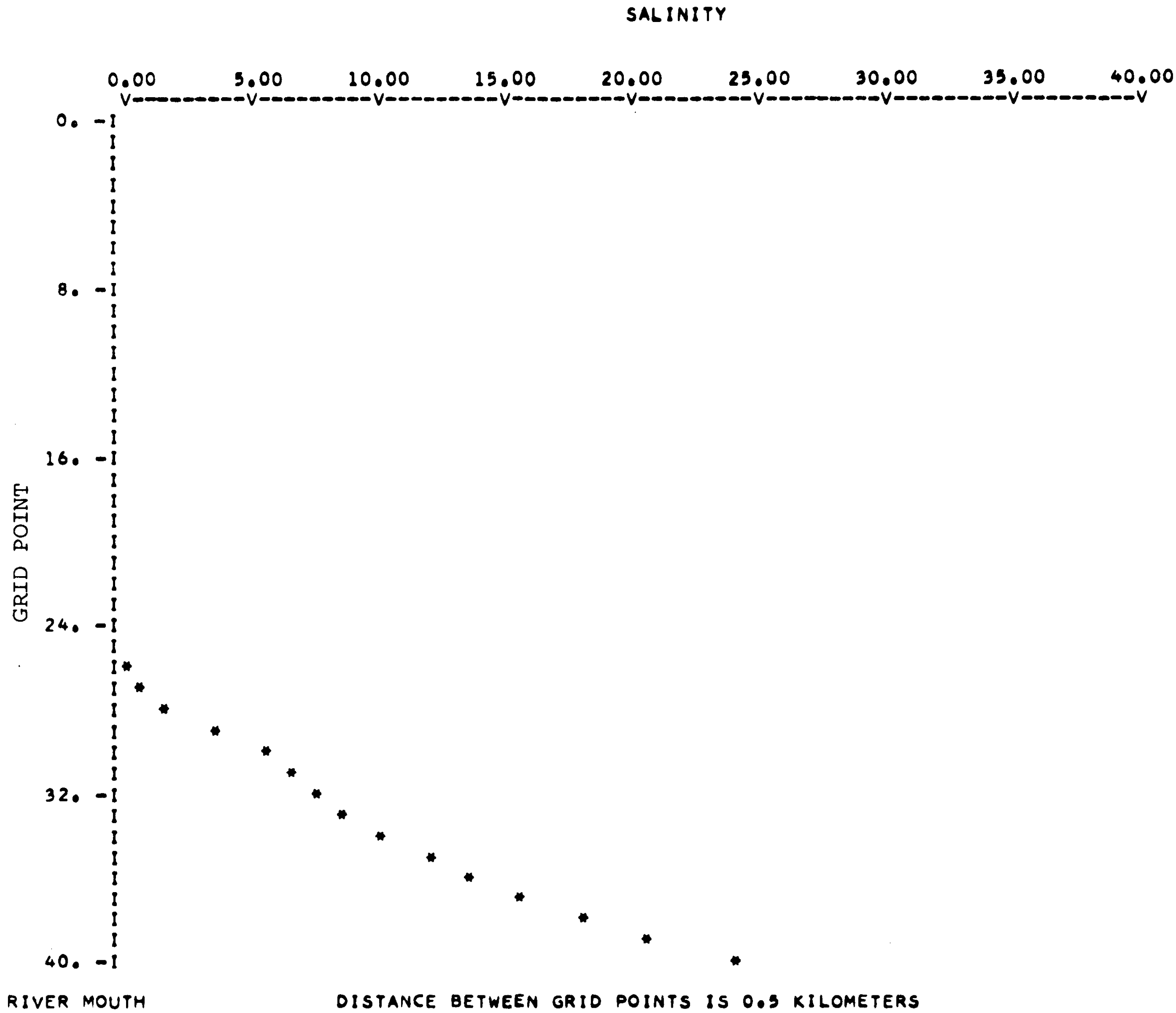


FIGURE A-25.

APPENDIX B

LOW TIDE SALINITY DISTRIBUTIONS

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 800. CFS

DISTRIBUTION AT LOW TIDE

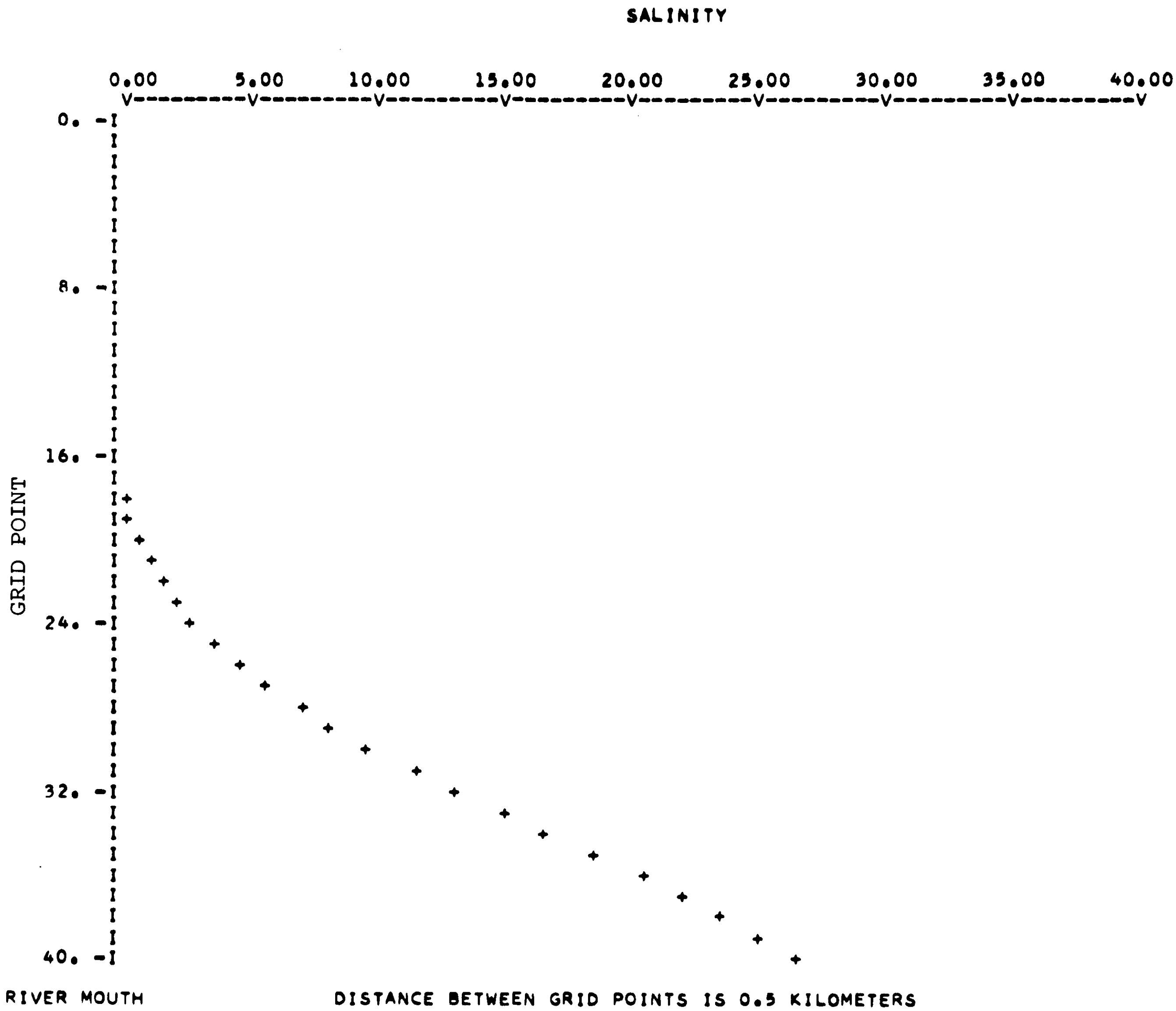
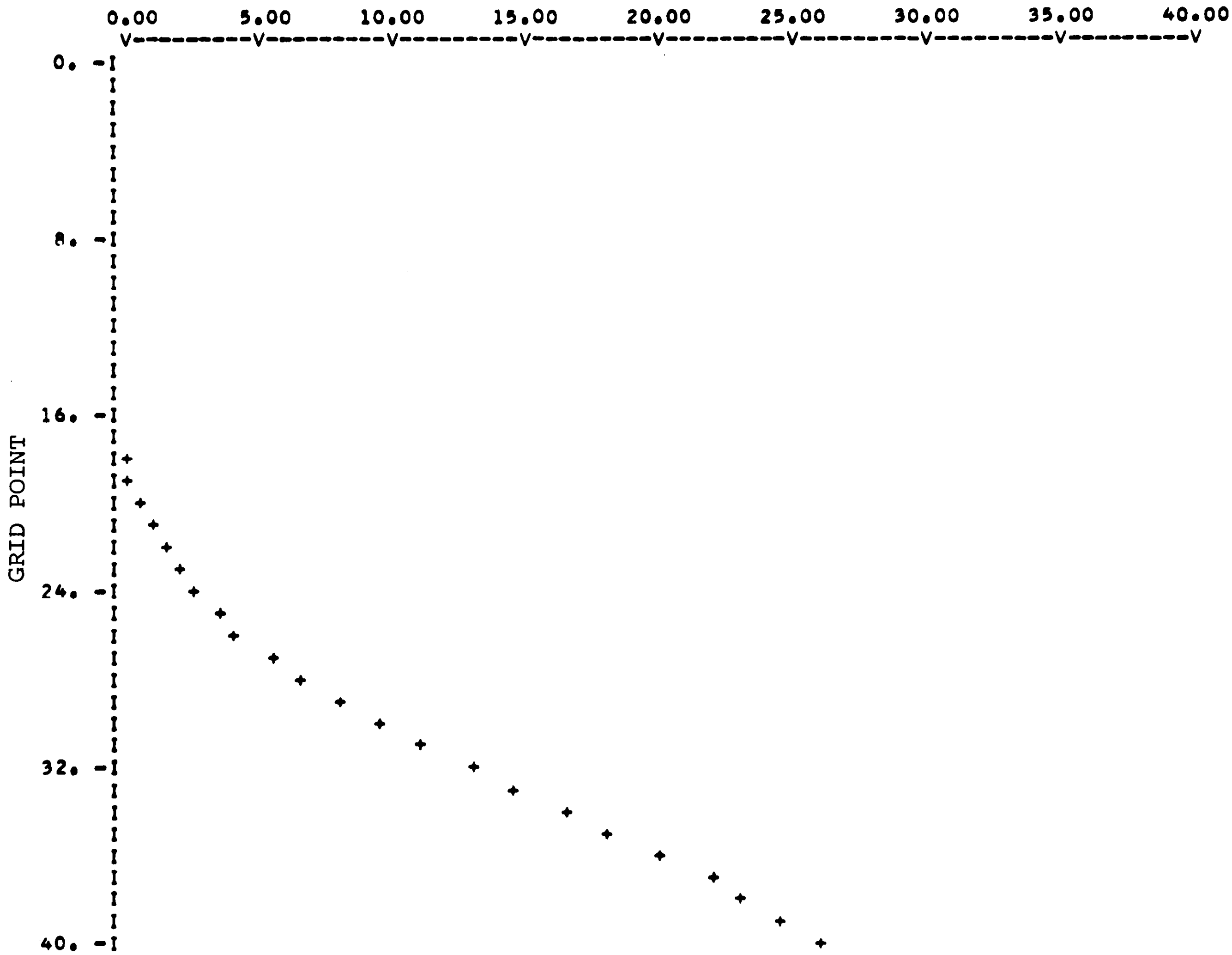


FIGURE B-1.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 850. CFS

DISTRIBUTION AT LOW TIDE

SALINITY



RIVER MOUTH DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-2.

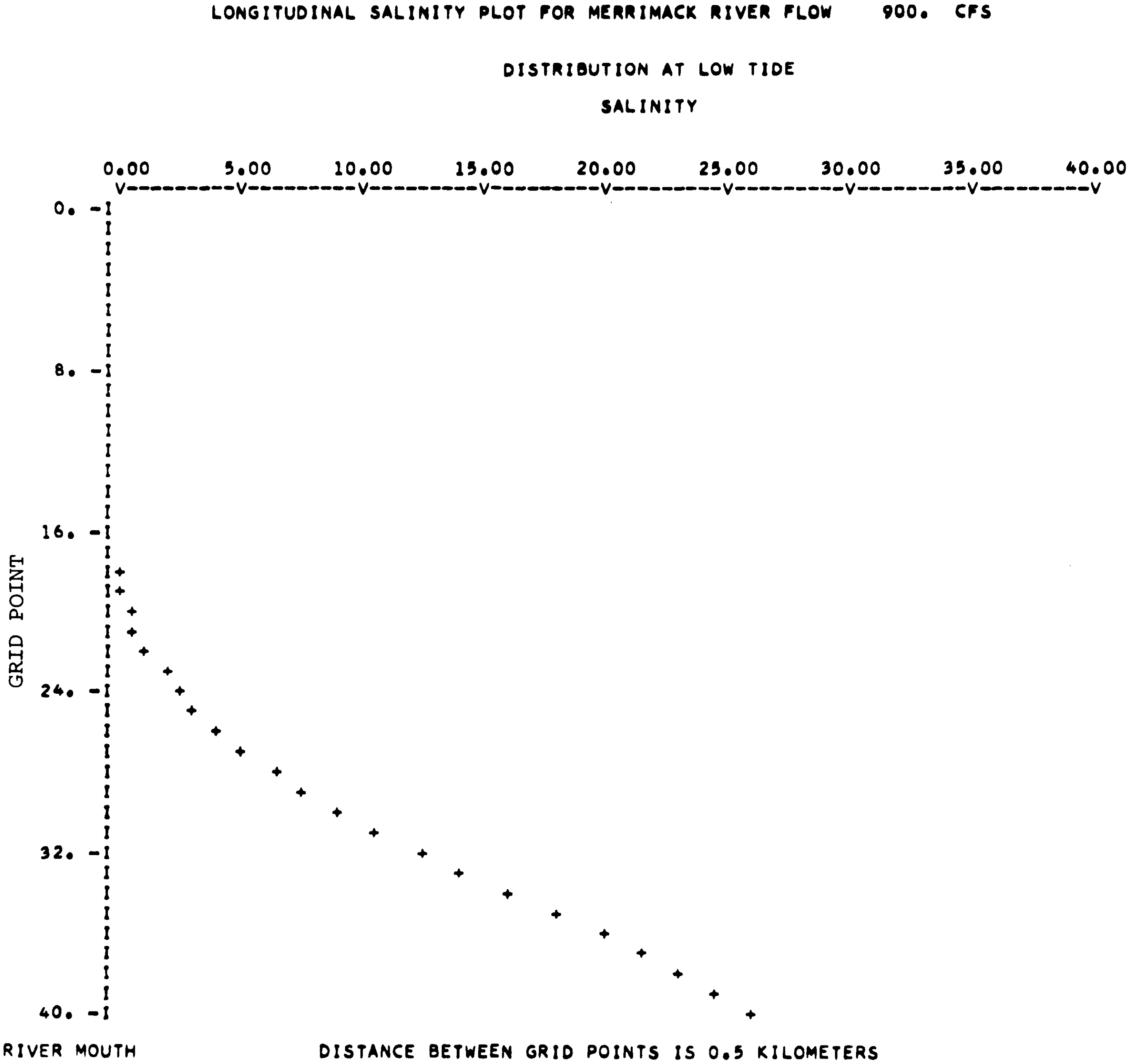

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 900. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-3.

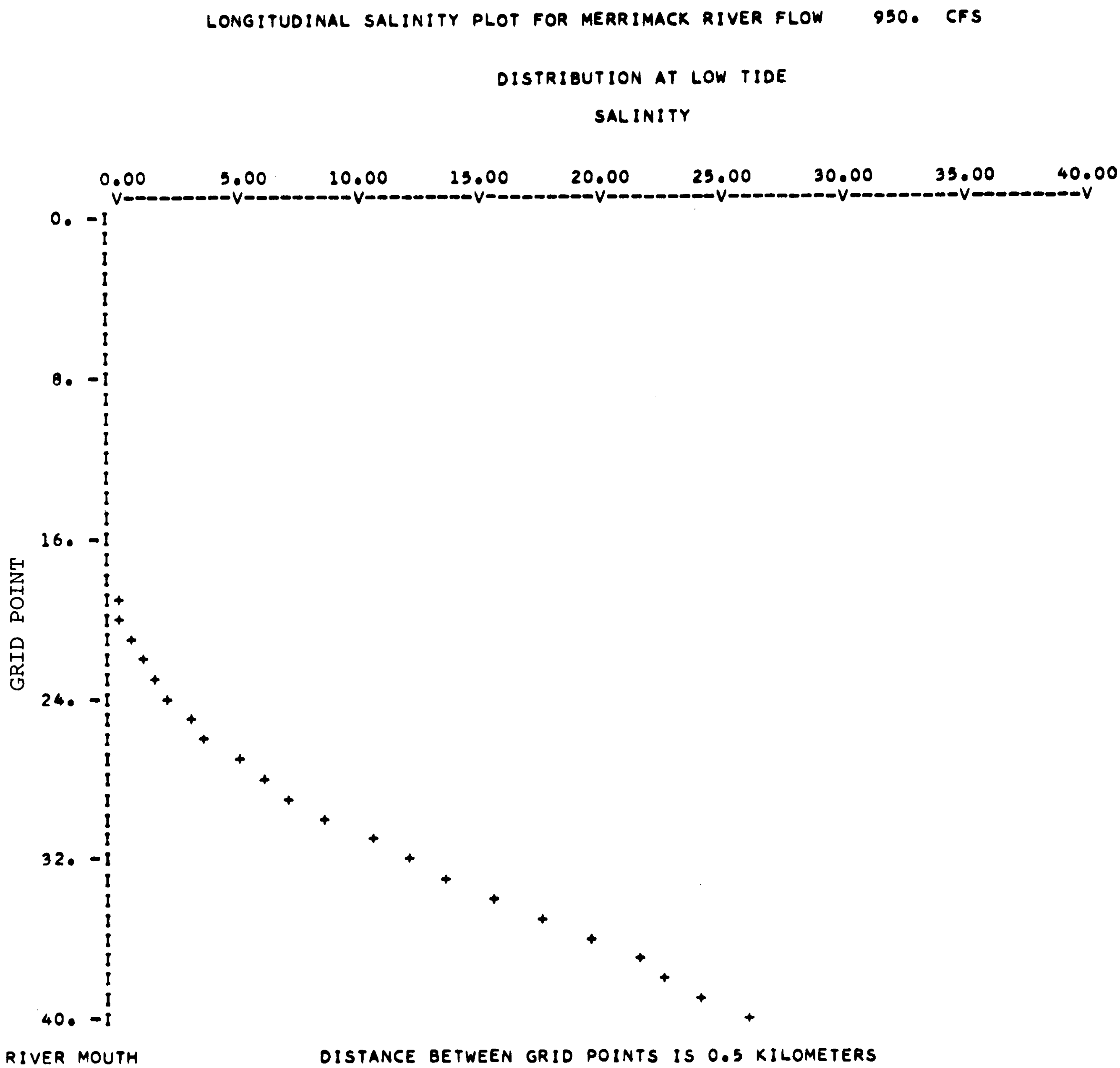
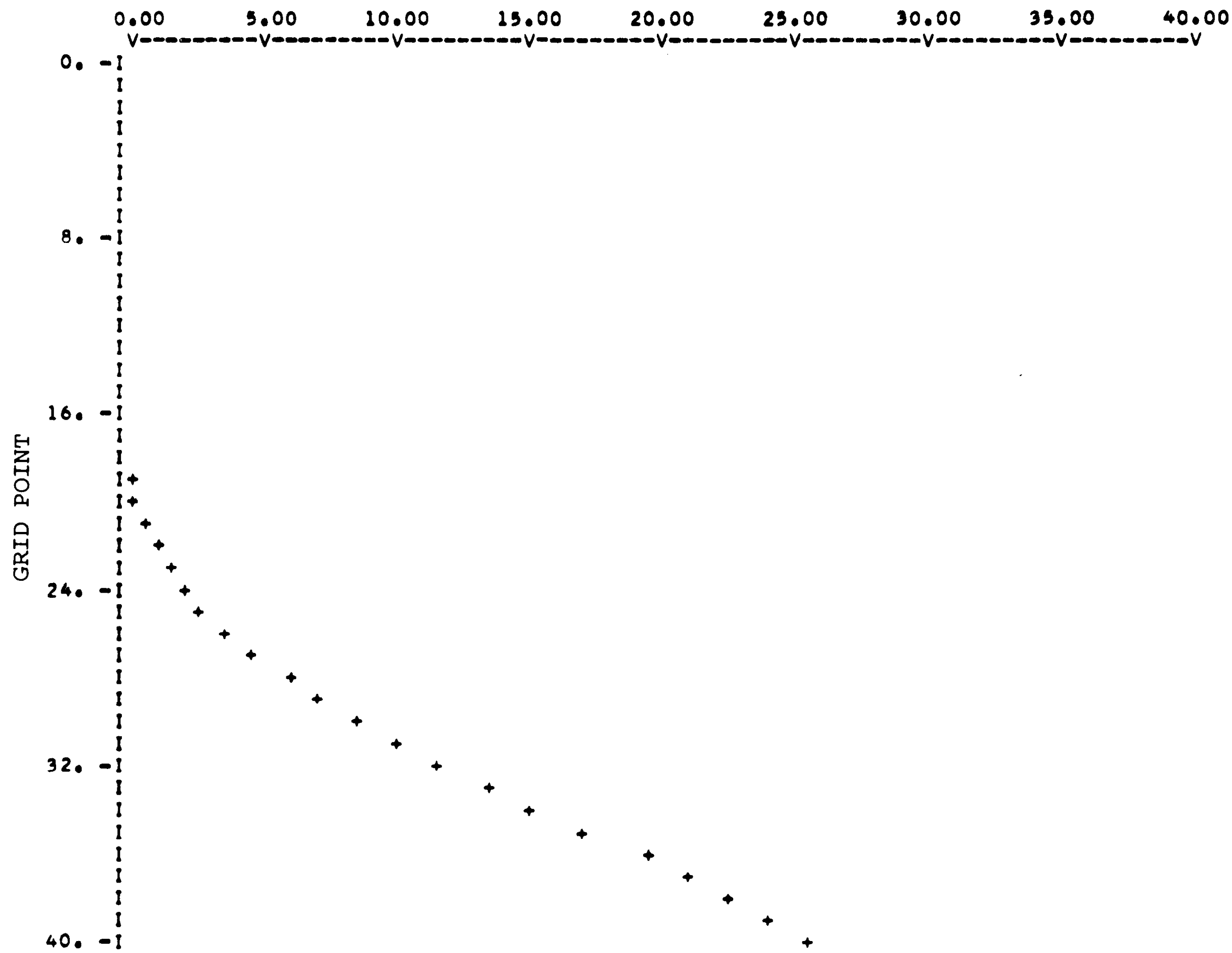

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 950. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-4.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1000. CFS

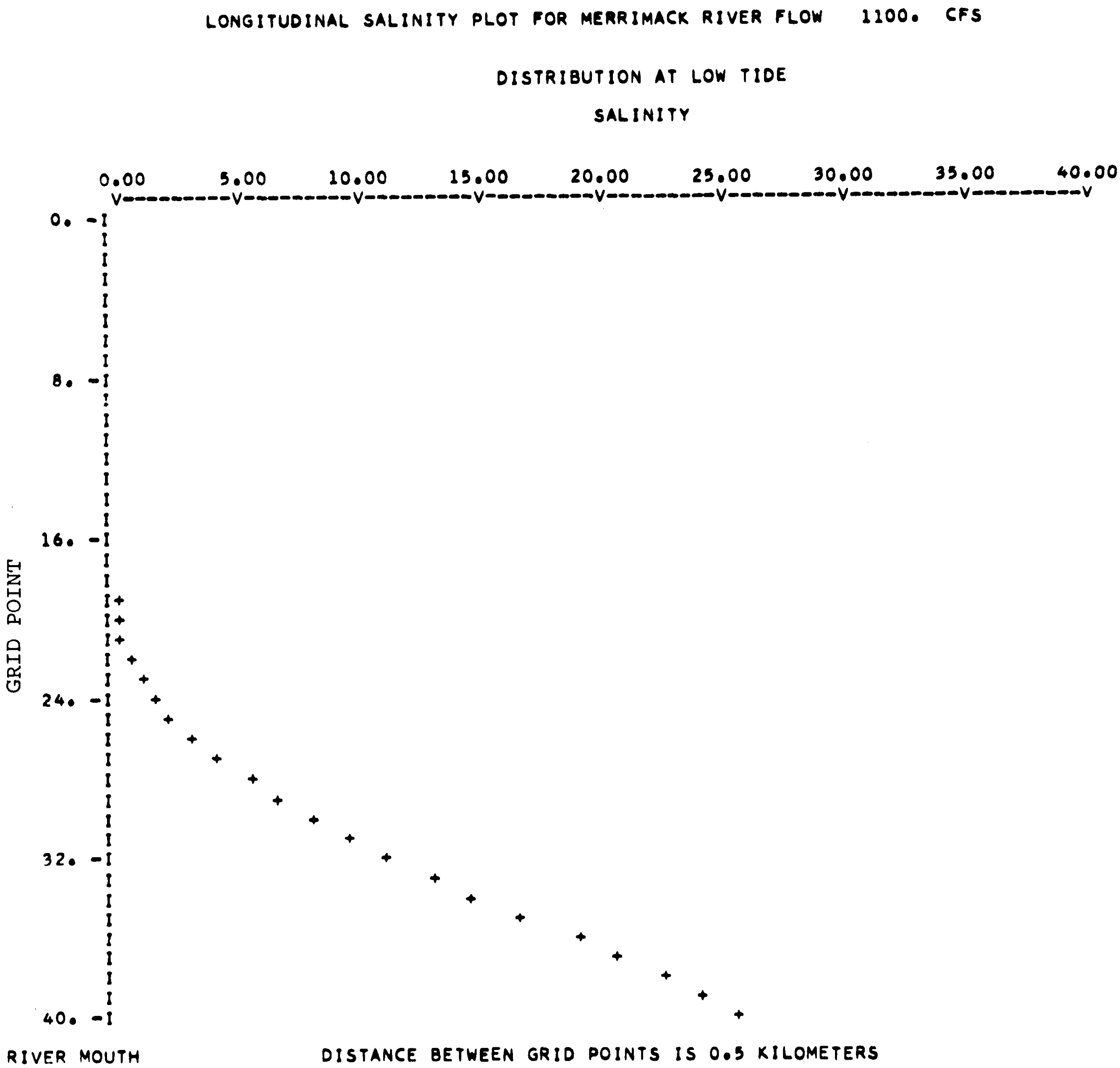
DISTRIBUTION AT LOW TIDE

SALINITY



RIVER MOUTH DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-5.



LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1100. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-6.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1200. CFS

DISTRIBUTION AT LOW TIDE

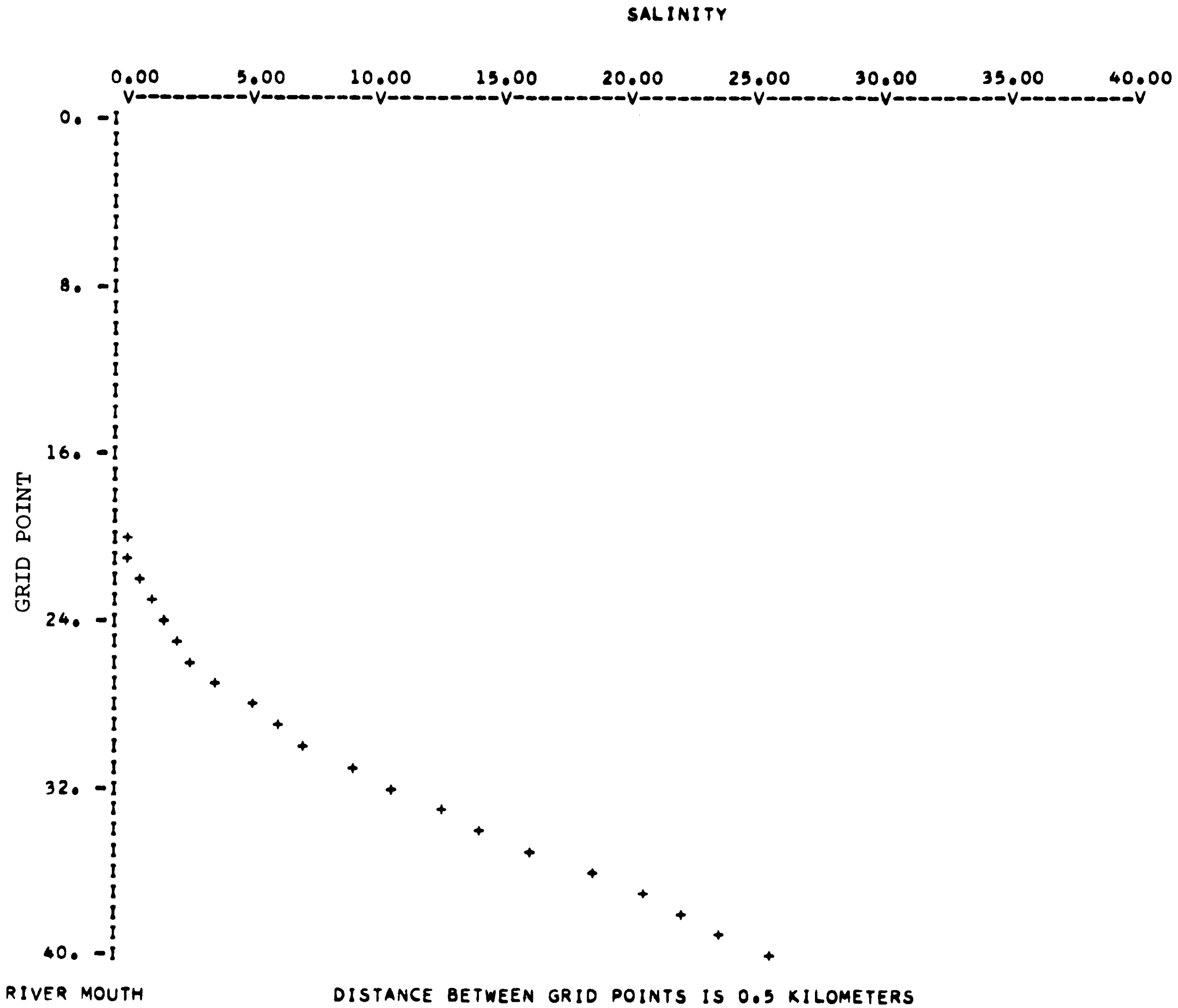
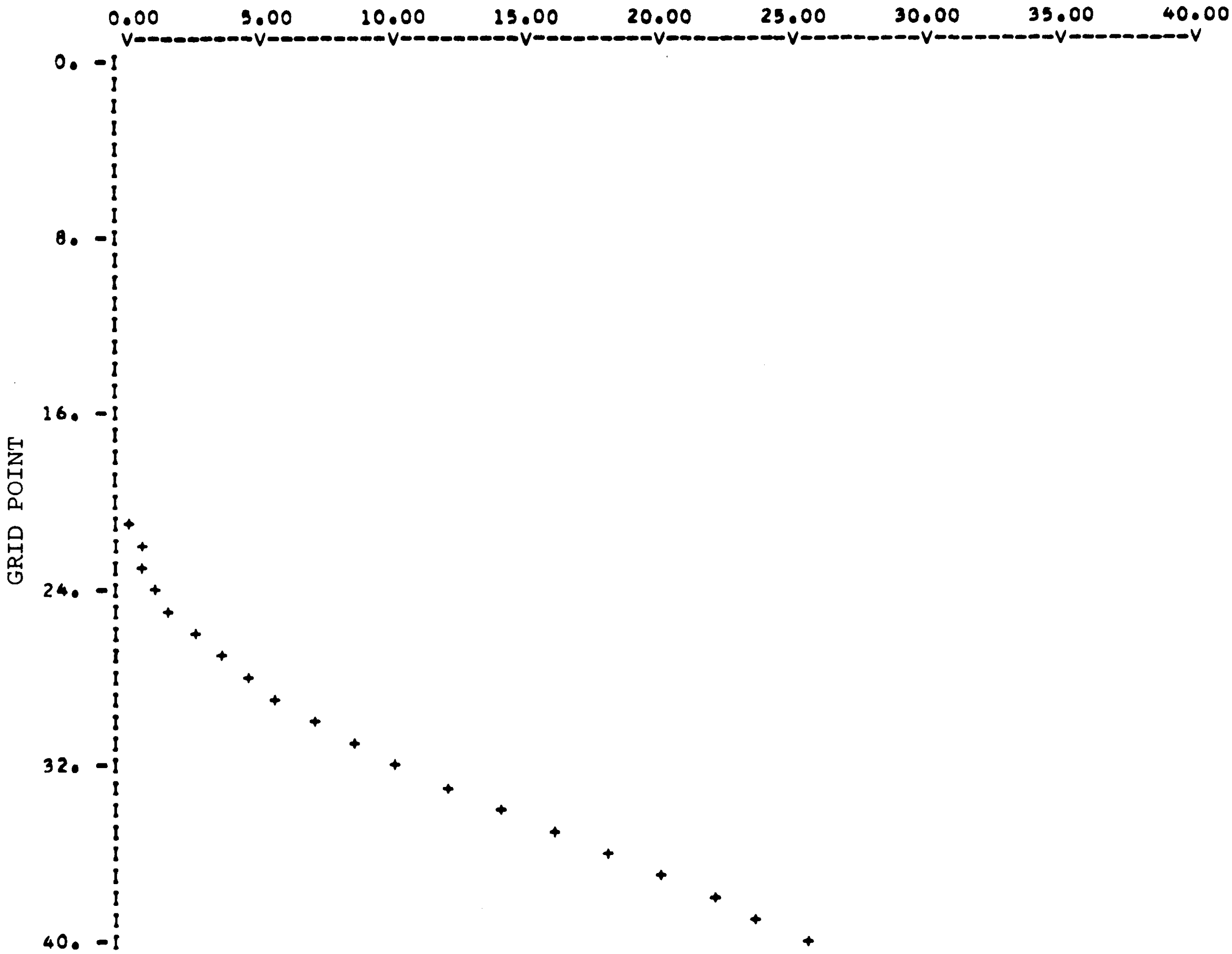


FIGURE B-7.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1300. CFS

DISTRIBUTION AT LOW TIDE

SALINITY



RIVER MOUTH DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-8.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1400. CFS

DISTRIBUTION AT LOW TIDE

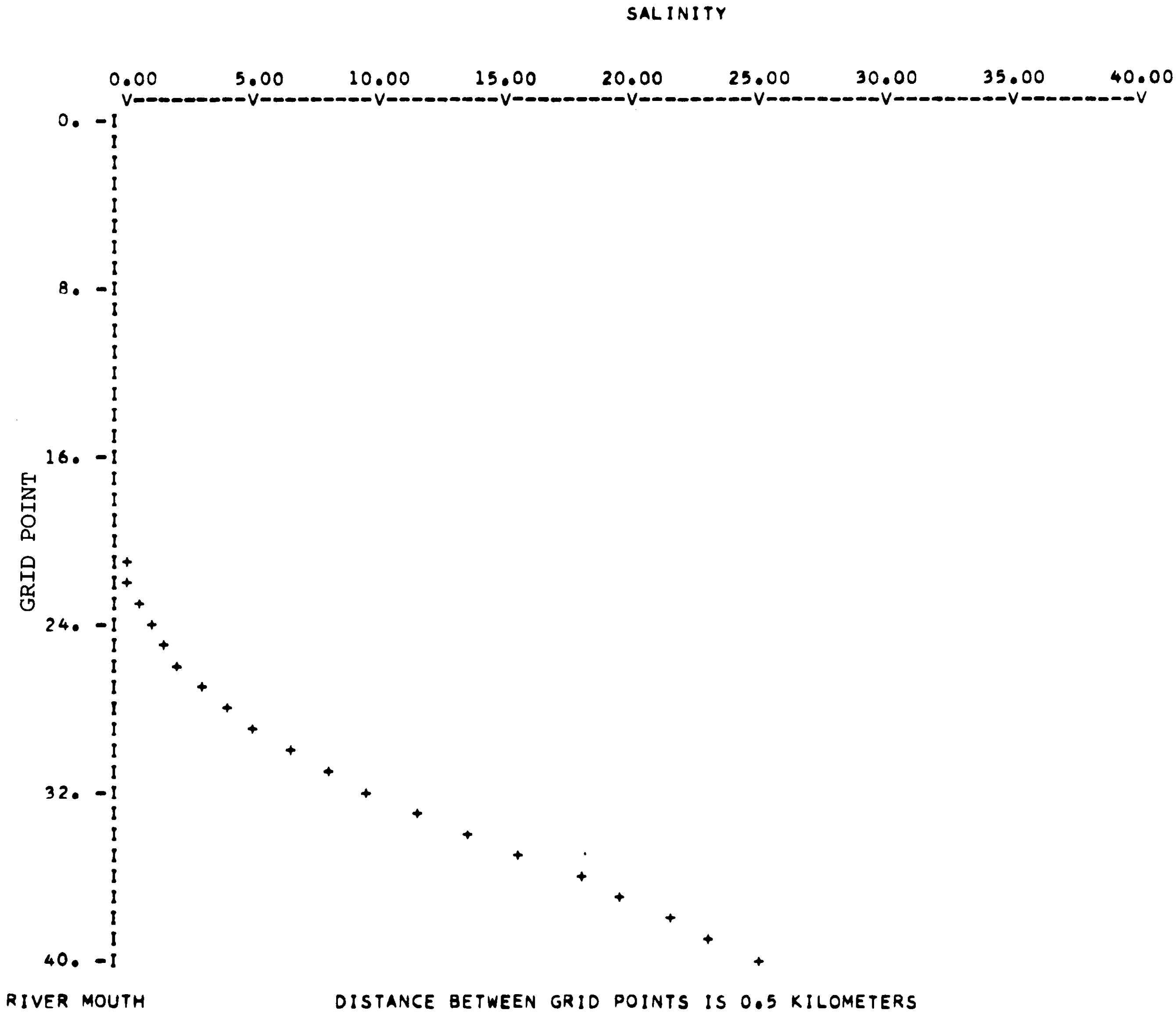


FIGURE B-9.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1500. CFS

DISTRIBUTION AT LOW TIDE

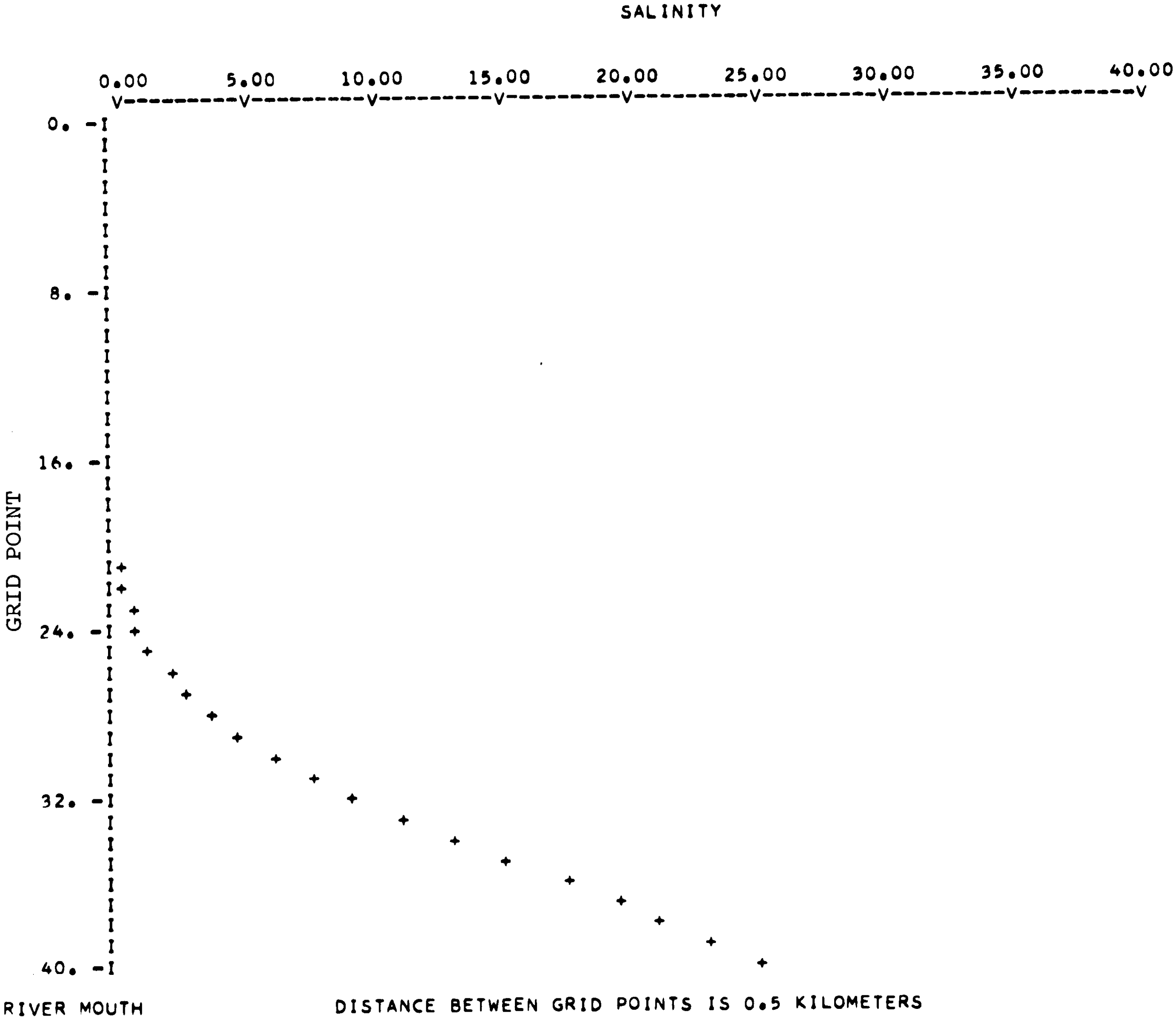


FIGURE B-10.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1600. CFS

DISTRIBUTION AT LOW TIDE

SALINITY

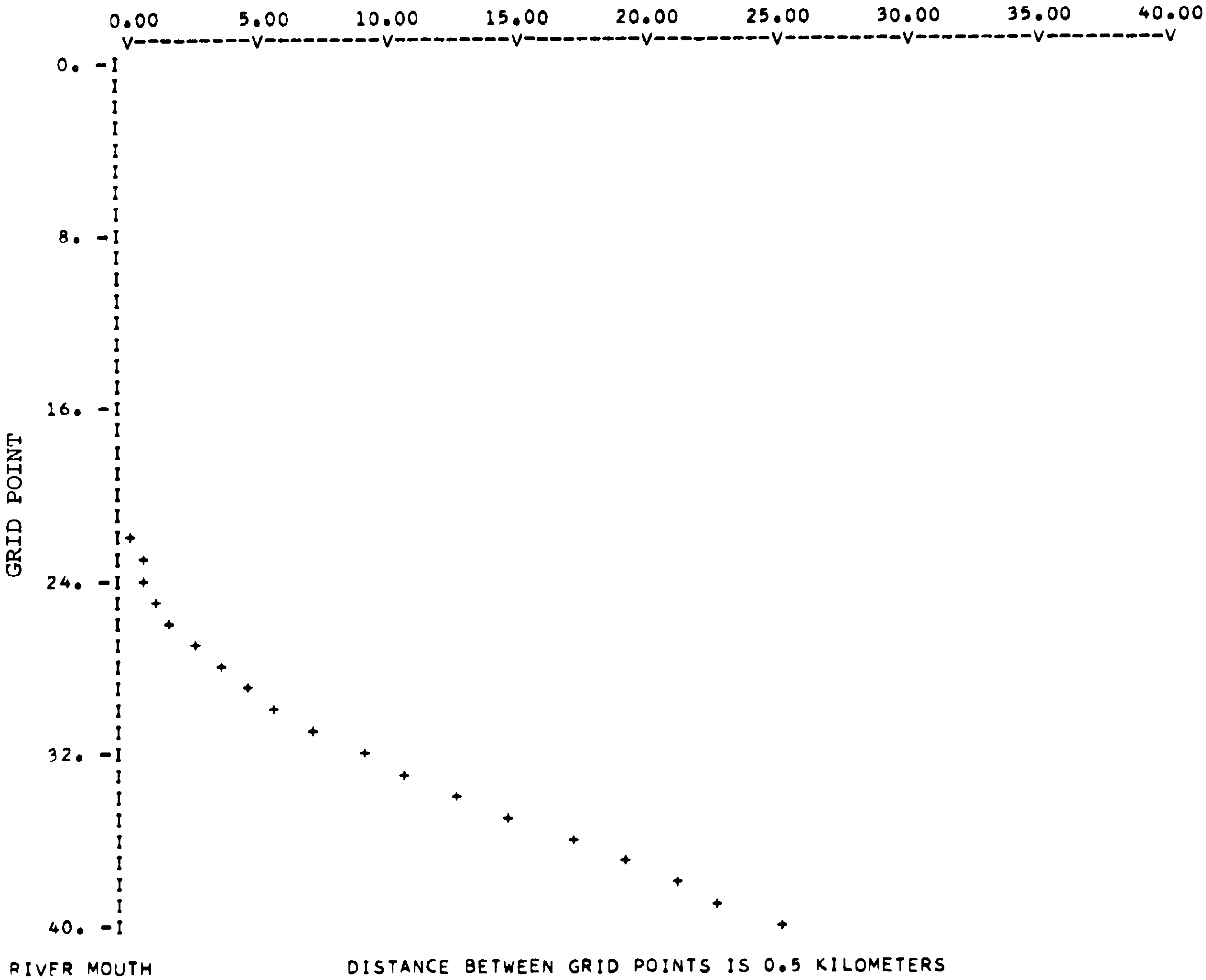


FIGURE B-11.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1700. CFS

DISTRIBUTION AT LOW TIDE

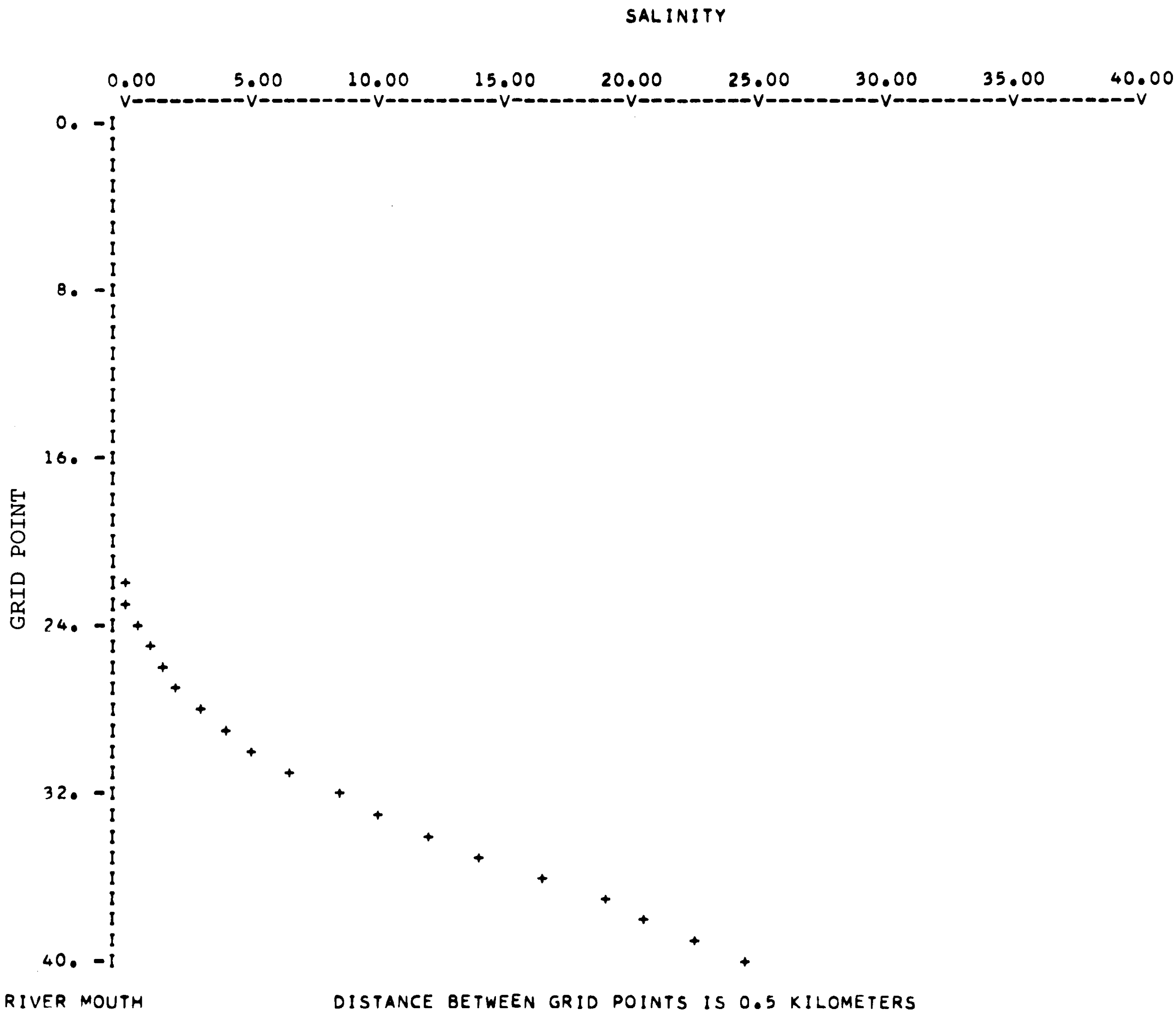


FIGURE B-12.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1800. CFS

DISTRIBUTION AT LOW TIDE

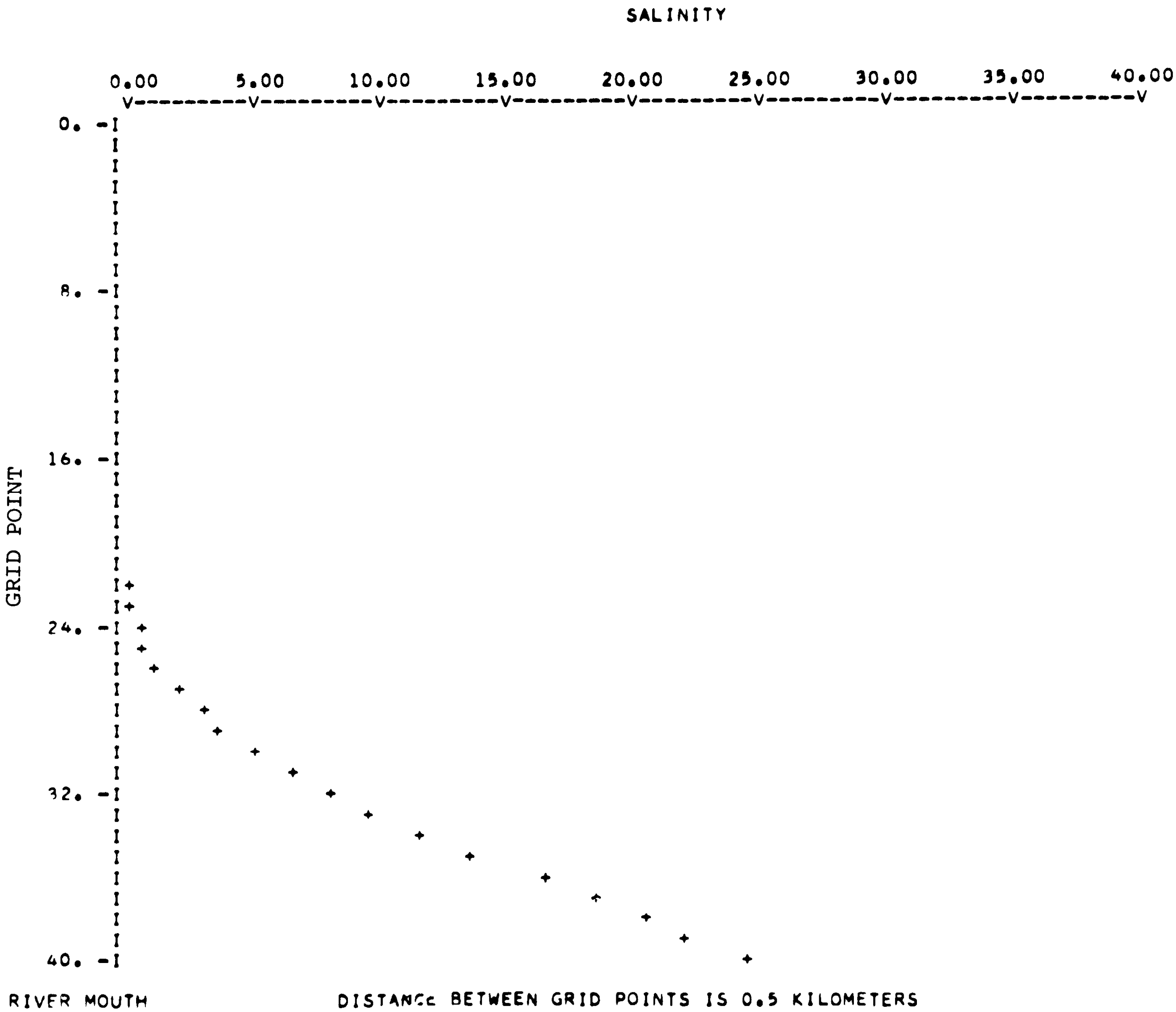


FIGURE B-13.

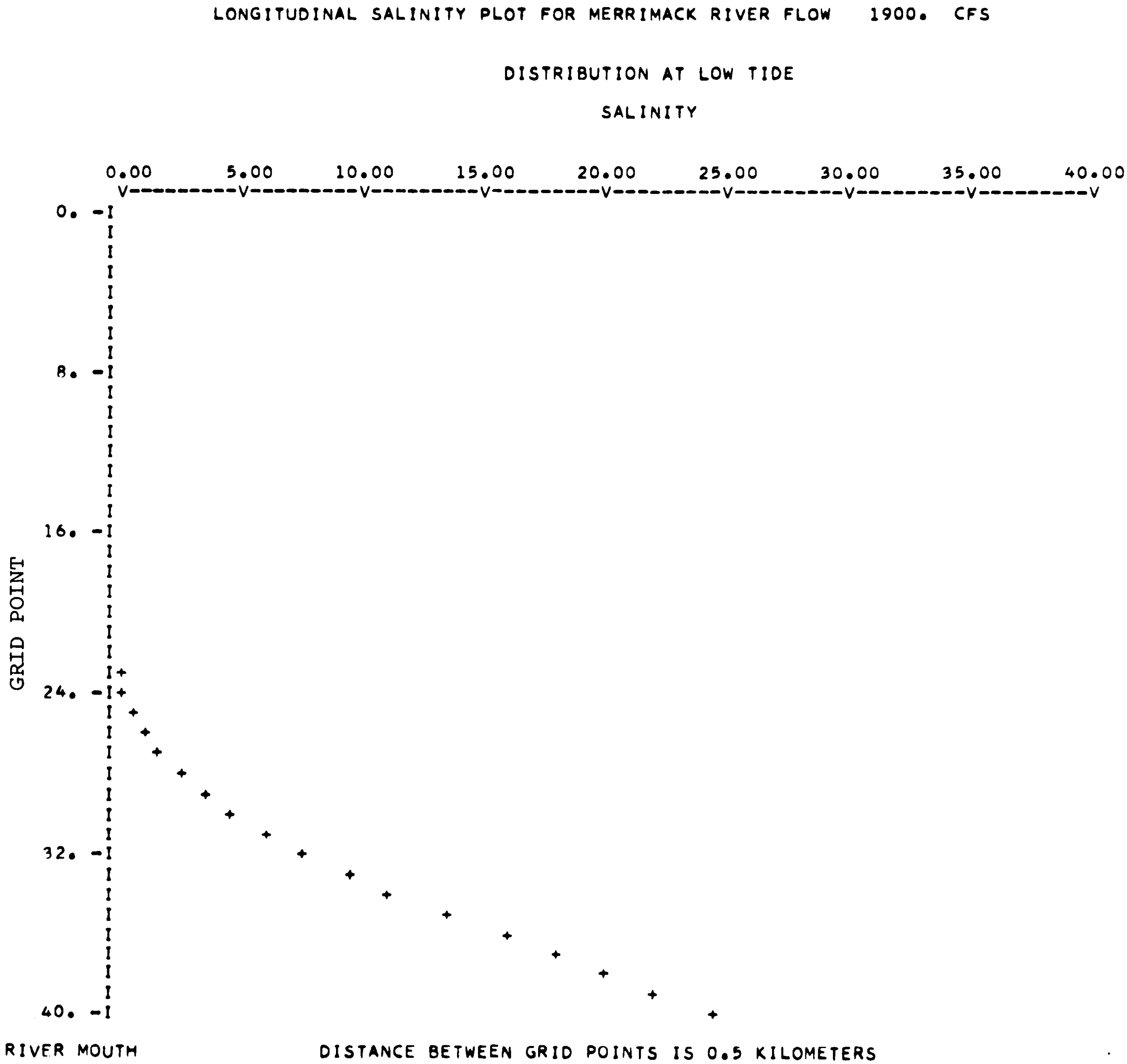

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 1900. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-14.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 2000. CFS

DISTRIBUTION AT LOW TIDE

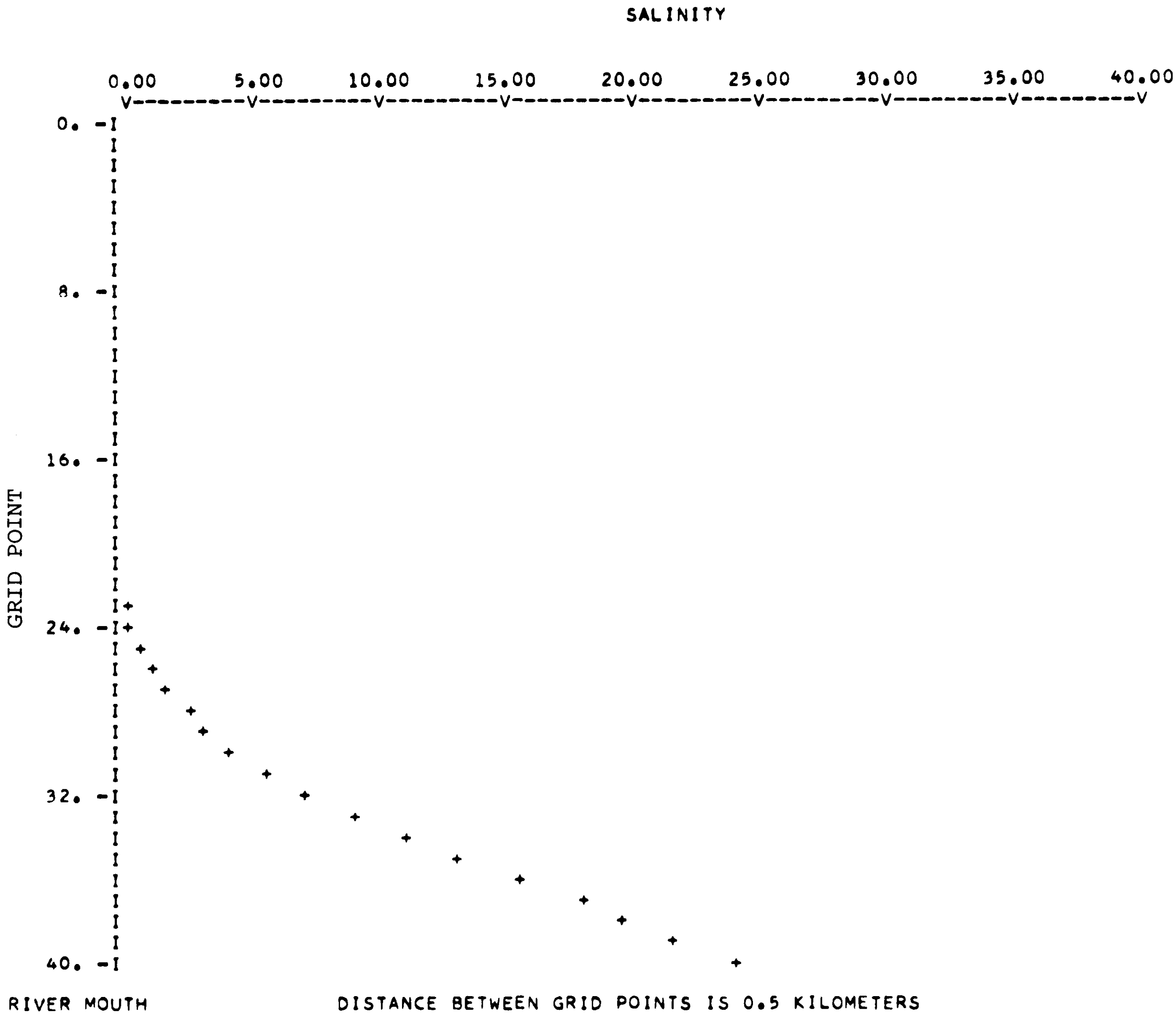


FIGURE B-15.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 3000. CFS

DISTRIBUTION AT LOW TIDE

SALINITY

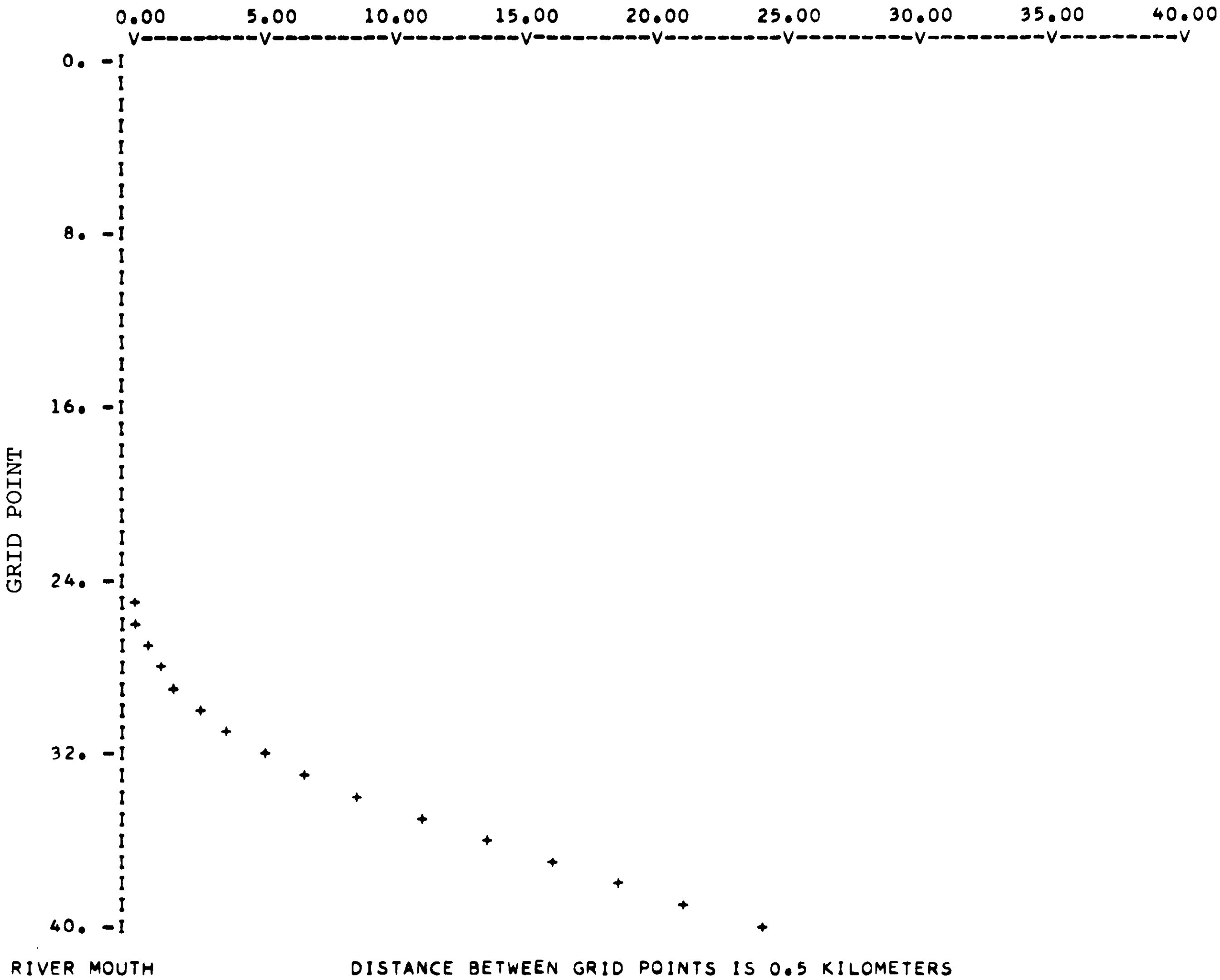
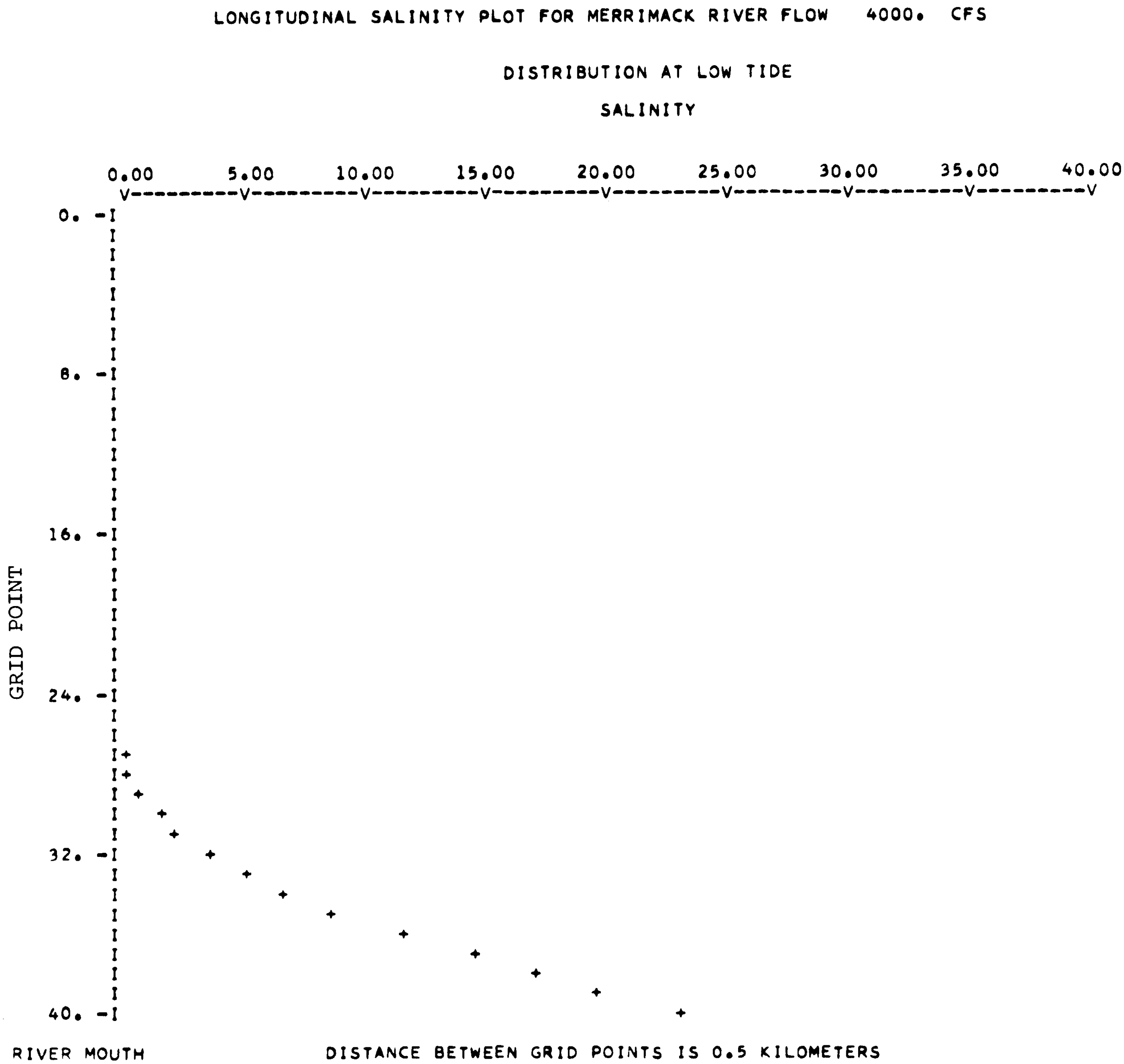


FIGURE B-16.



LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 4000. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-17.

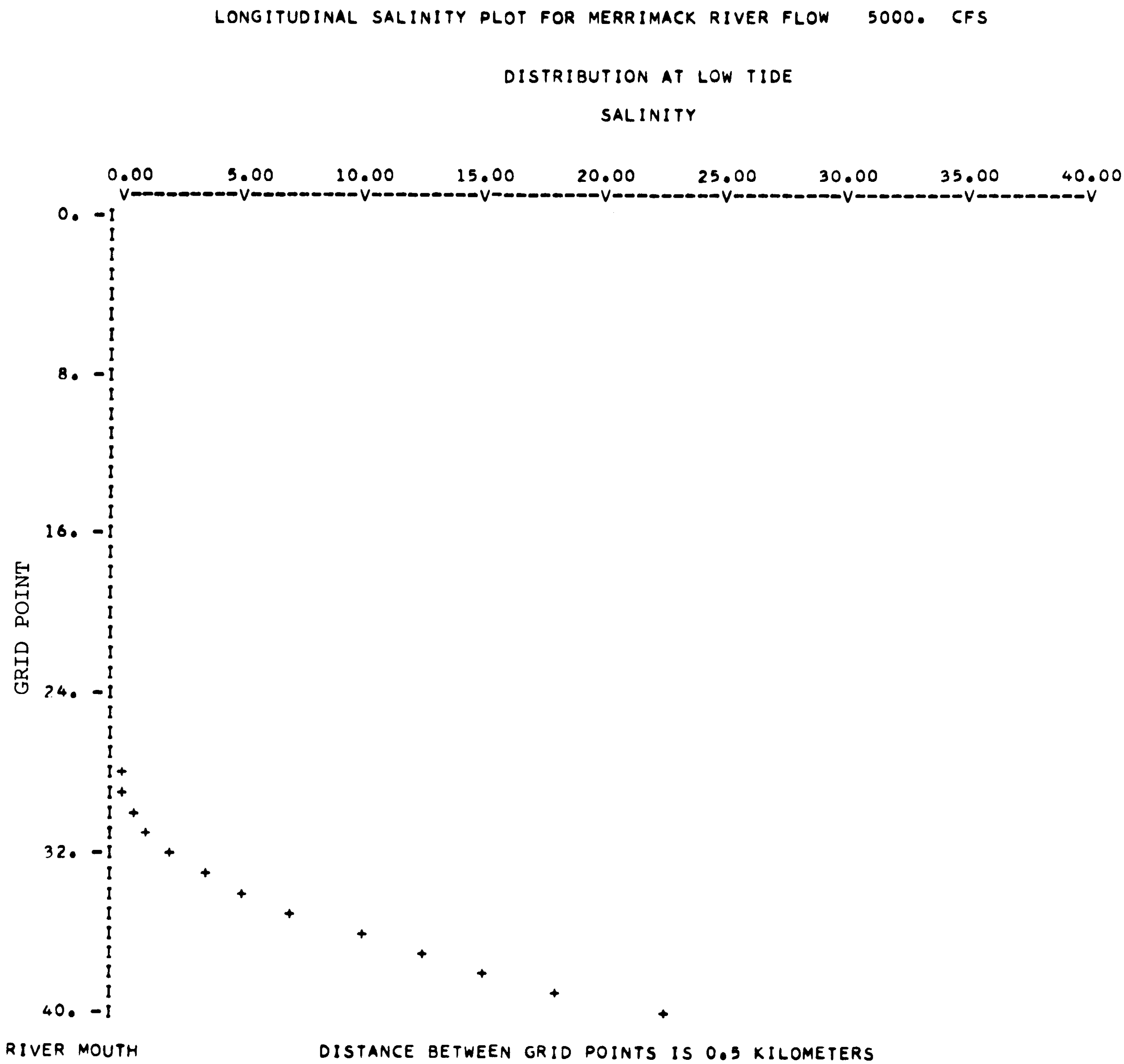

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 5000. CFS
DISTRIBUTION AT LOW TIDE
SALINITY
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
0.
8.
16.
24.
32.
40.
GRID POINT
RIVER MOUTH
DISTANCE BETWEEN GRID POINTS IS 0.5 KILOMETERS

FIGURE B-18.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 6000. CFS

DISTRIBUTION AT LOW TIDE

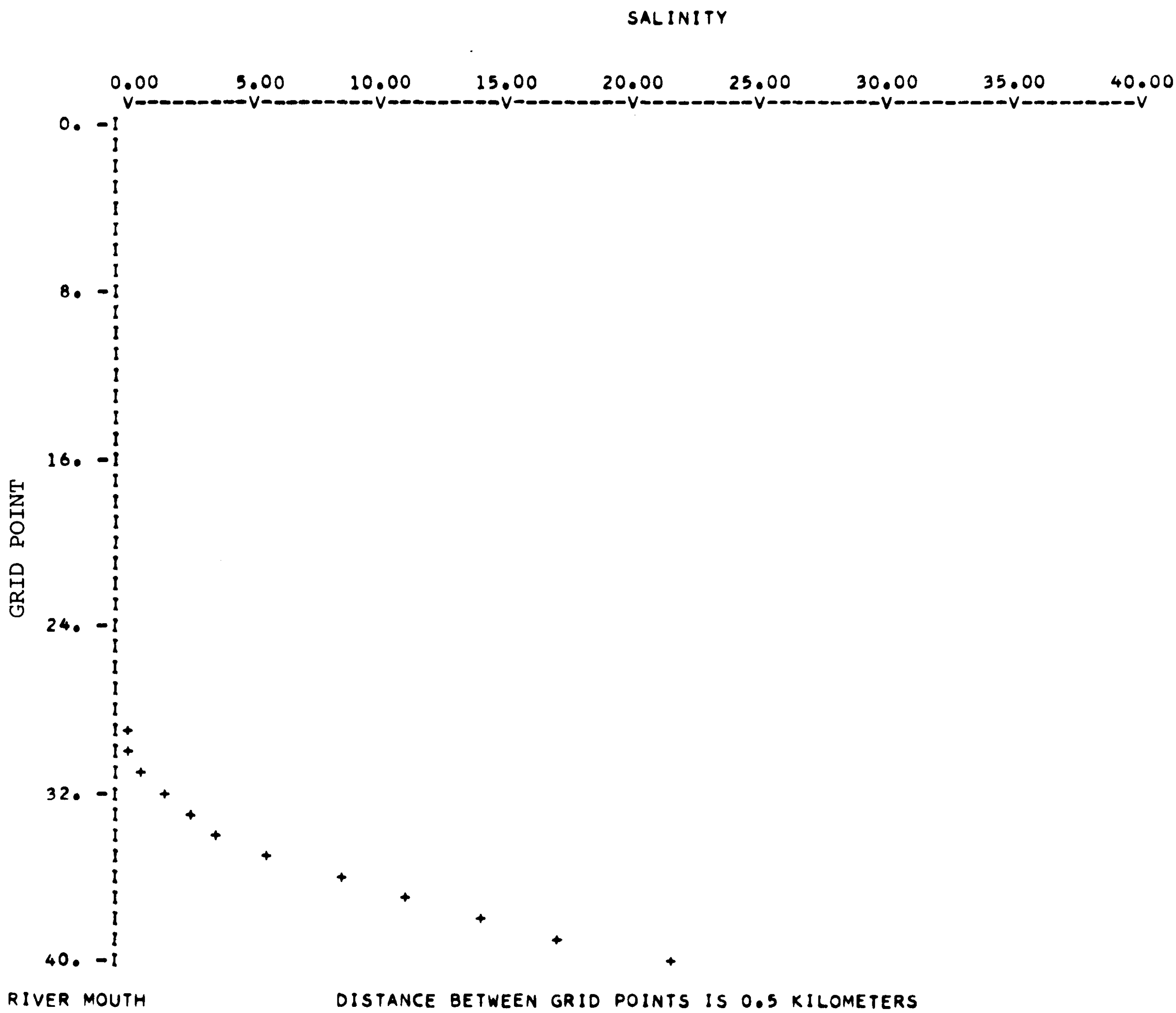


FIGURE B-19.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 7000. CFS

DISTRIBUTION AT LOW TIDE

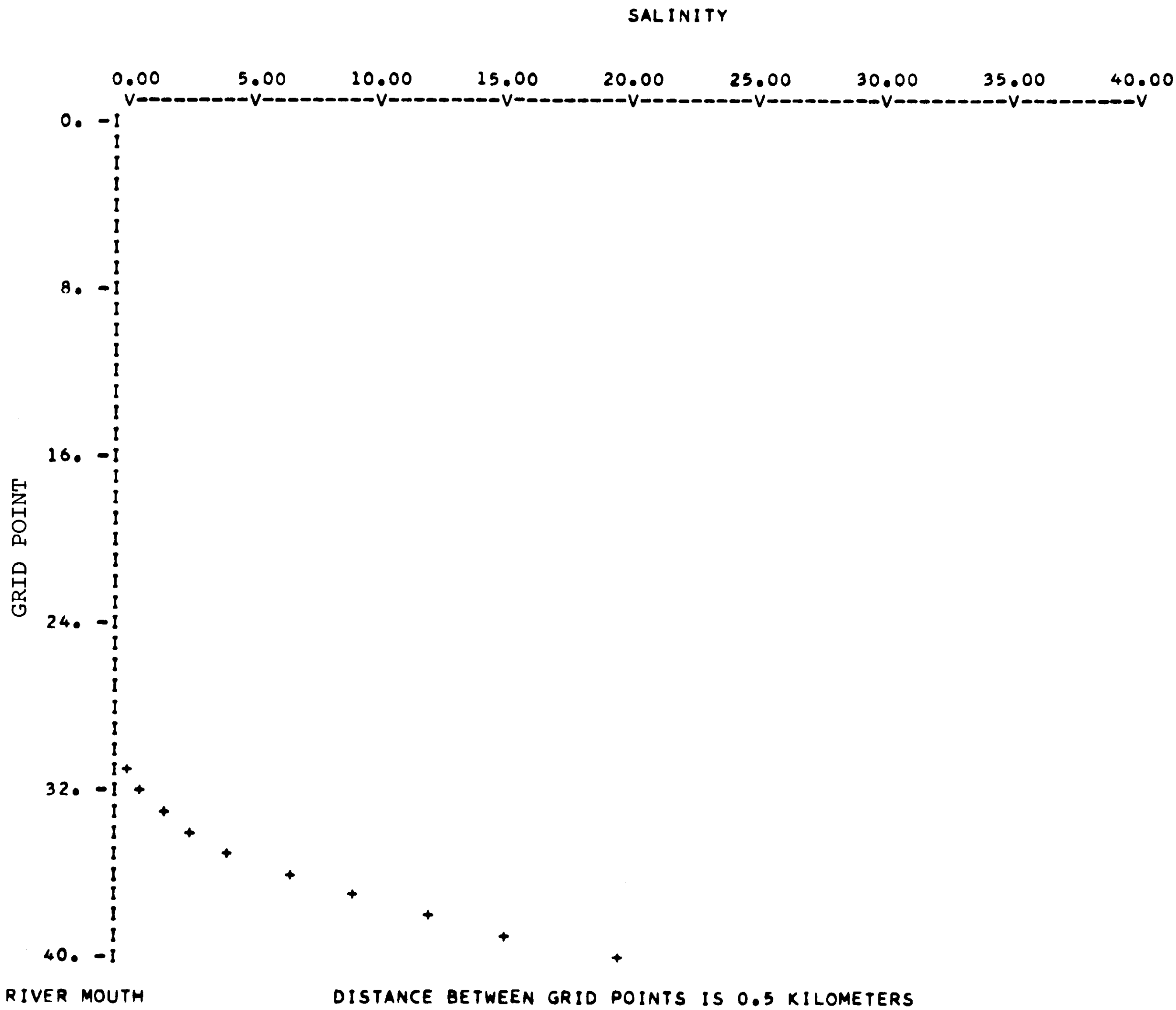


FIGURE B-20.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 8000. CFS

DISTRIBUTION AT LOW TIDE

SALINITY

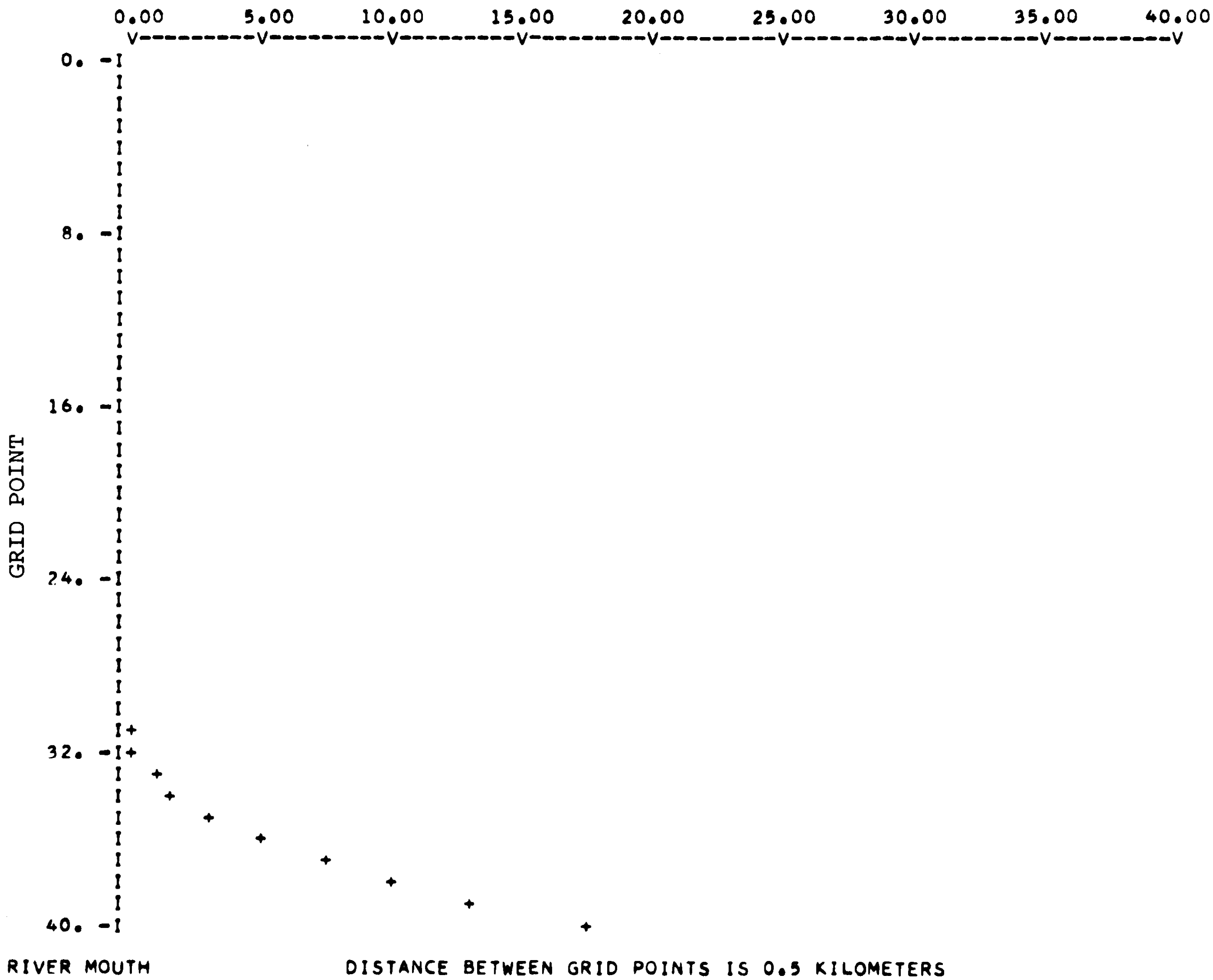


FIGURE B-21.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 10000. CFS

DISTRIBUTION AT LOW TIDE

SALINITY

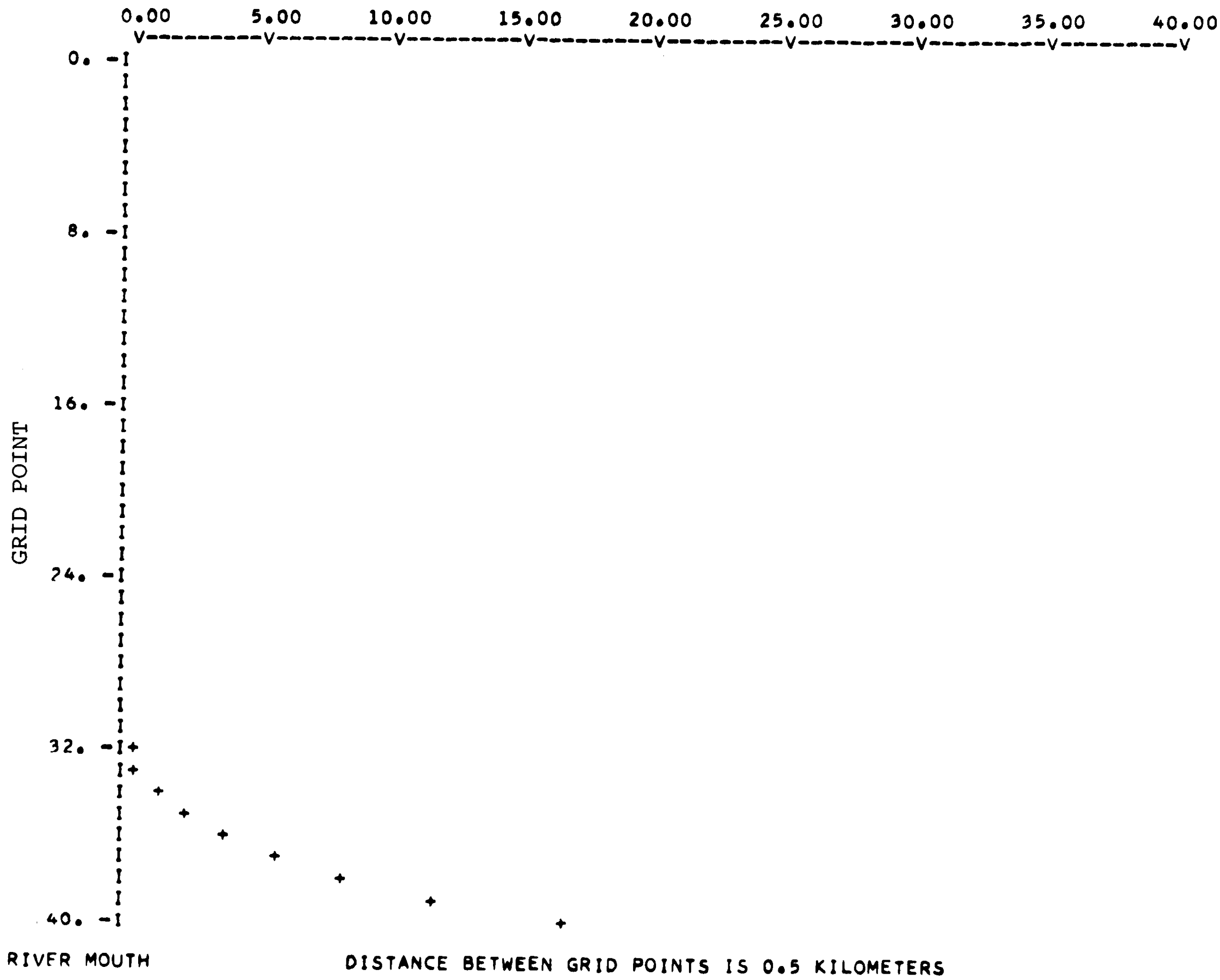


FIGURE B-22.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 12000. CFS

DISTRIBUTION AT LOW TIDE

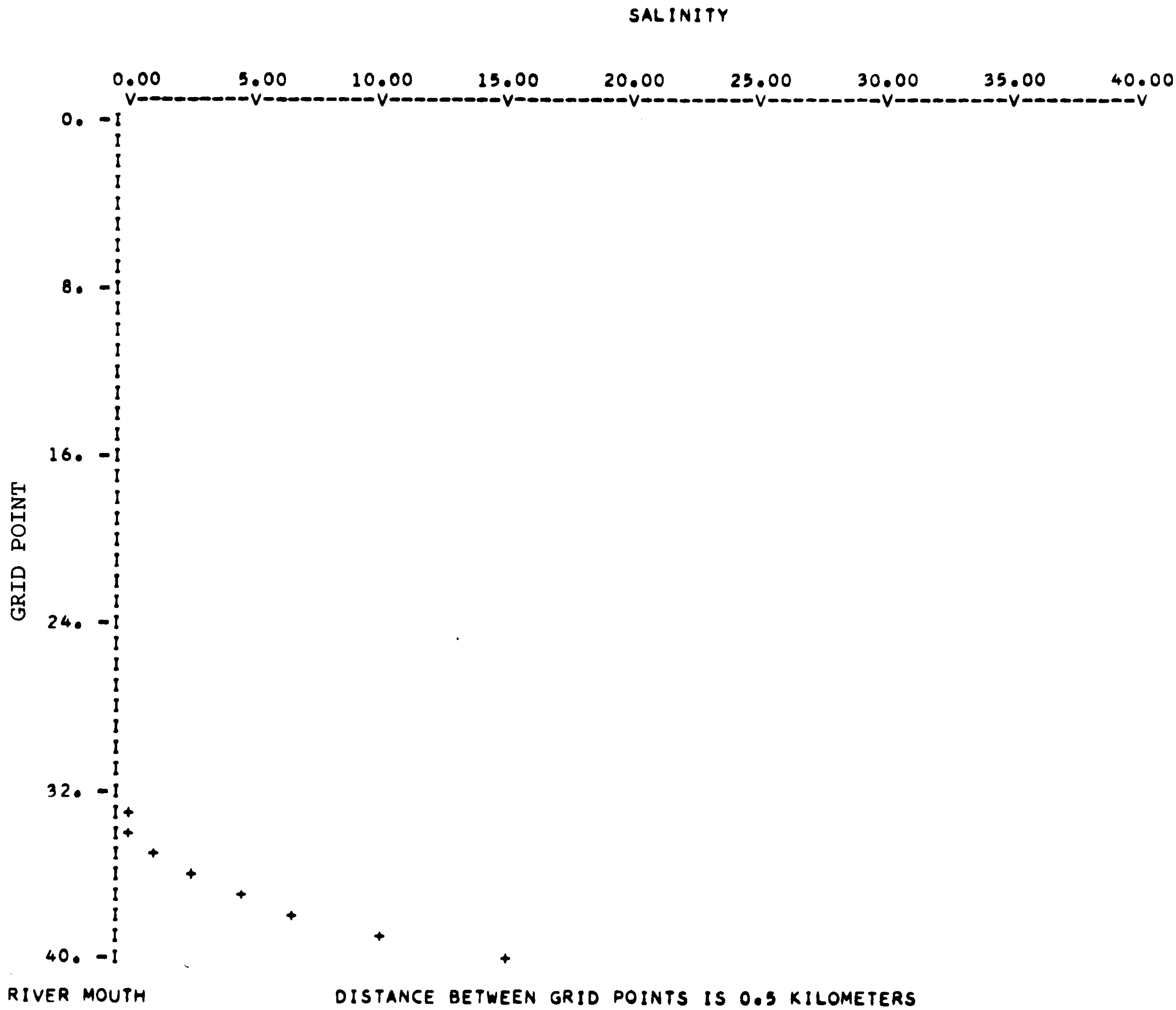


FIGURE B-23.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 14000. CFS

DISTRIBUTION AT LOW TIDE

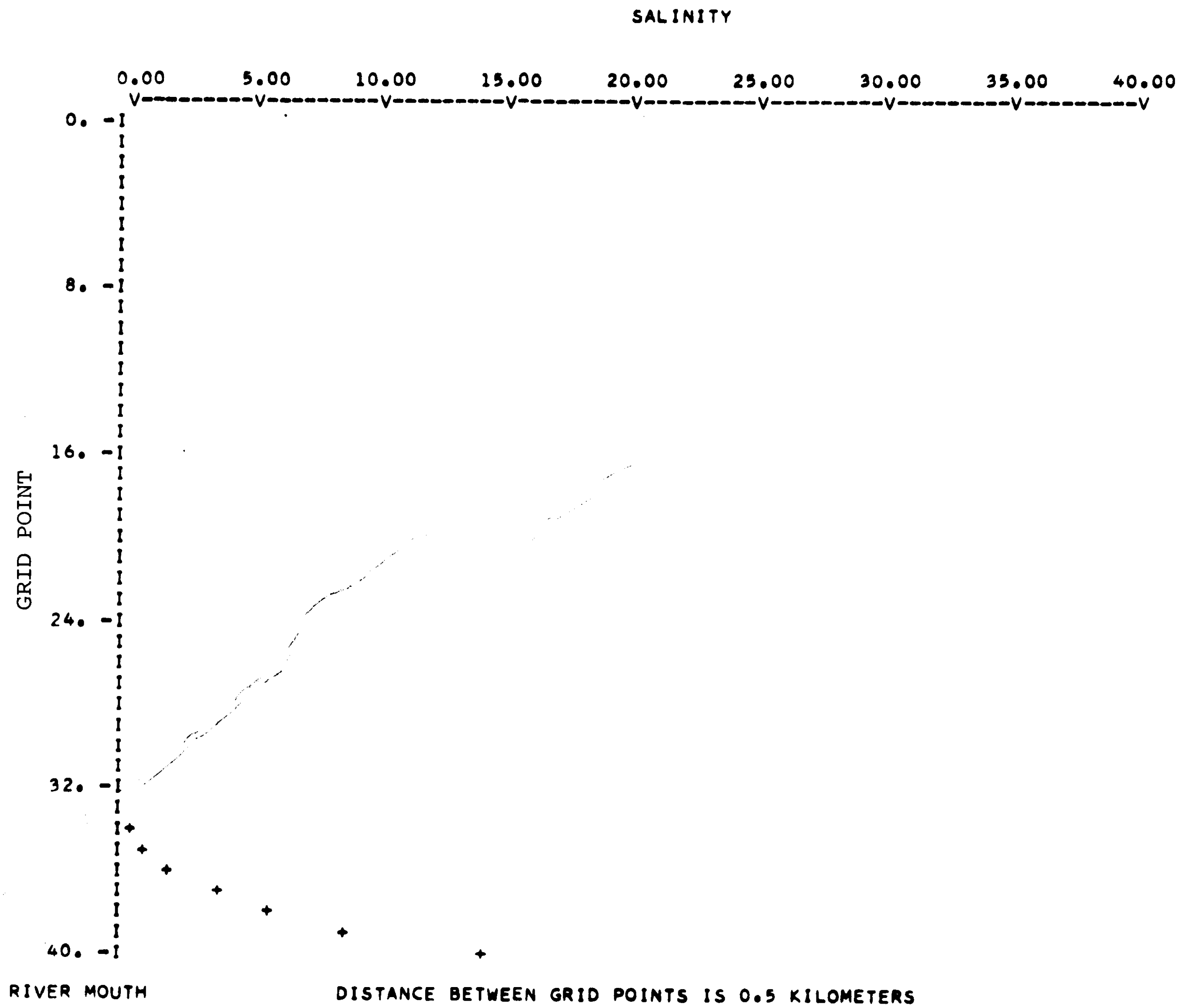


FIGURE B-24.

LONGITUDINAL SALINITY PLOT FOR MERRIMACK RIVER FLOW 16000. CFS

DISTRIBUTION AT LOW TIDE

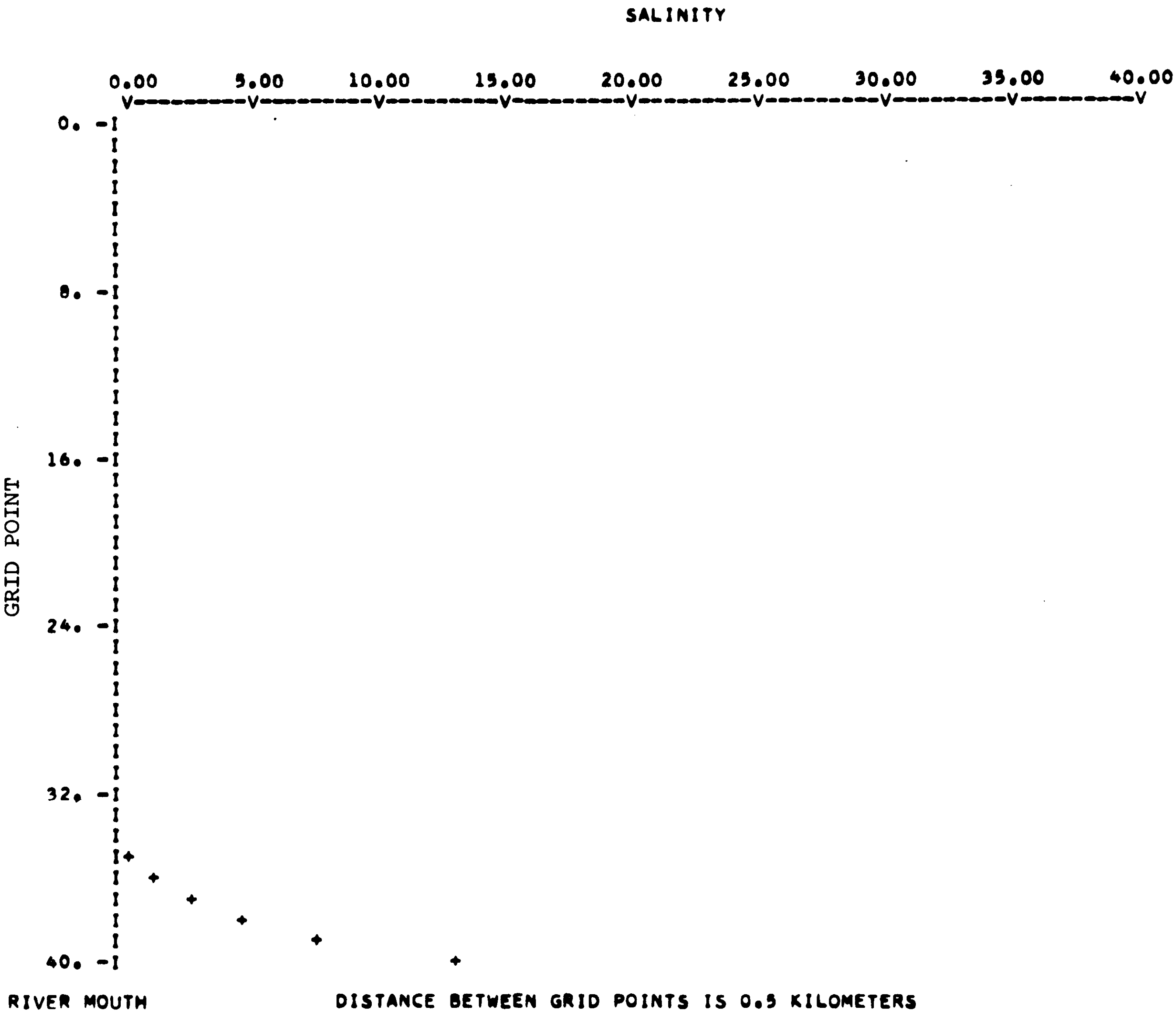


FIGURE B-25.

APPENDIX C

AVERAGE WEEKLY FLOW RATES 1927-1967

AVERAGE WEEKLY FLOW RATES CFS 1927

		1	2	3	4	5
1	4114	23714	7857	3375	4305	13542
2	3507	25057	6705	2961	8035	8428
3	3958	12142	5021	2525	7984	
4	6111	9957	3810	2600	8202	
5	6187	8020	2462	6655	32767	
6	4890	8611	2443	8000	11357	
7	4227	10201	2215	4180	15485	
8	4430	5985	2840	3740	13314	
9	5491	6145	4128	2925	13871	
10	7035	8057	3001	3065	18414	

AVERAGE WEEKLY FLOW RATES CFS 1928

		1	2	3	4	5
1	9628	7612	14900	7167	2987	4610
2	8385	8270	15142	7325	3130	4131
3	6972	14428	12157	5104	4120	
4	9345	12542	12171	3781	3588	
5	7284	21128	7934	9065	3597	
6	6838	12200	7565	7215	3310	
7	10454	15814	9802	5244	4231	
8	9782	22657	4935	5874	3194	
9	8294	14557	5308	4824	4087	
10	5394	8690	5870	3697	3577	

AVERAGE WEEKLY FLOW RATES CFS 1929

		1	2	3	4	5
1	4920	19028	13528	1700	1531	2781
2	6310	25242	7860	1583	1384	2477
3	6790	19842	4695	2064	2300	
4	7034	16757	3857	1698	1822	
5	4457	17928	3855	1402	1678	
6	8415	20857	4884	1535	2294	
7	6021	23742	3301	2018	3380	
8	4515	26142	2604	1787	2000	
9	5055	18814	2175	1248	1672	
10	11777	15657	1939	1647	1538	

AVERAGE WEEKLY FLOW RATES CFS 1930

		1	2	3	4	5
1	2715	11845	5375	2005	1101	1789
2	6611	8527	5954	1748	1164	1955
3	5058	16914	3652	3072	1625	
4	3465	11497	7117	2697	1944	
5	2684	14842	6224	1891	1935	
6	2697	9630	3607	1832	2407	
7	3115	6954	2652	1685	4981	
8	6890	6794	2313	1440	3268	
9	9650	6508	2197	1220	3307	
10	11337	4945	1938	1079	2395	

AVERAGE WEEKLY FLOW RATES CFS 1931

		1	2	3	4	5
1	1890	5684	10752	2318	1520	4404
2	1991	7760	7812	1889	2177	9370
3	1807	18171	8868	3252	2077	
4	1666	22185	19128	2087	3641	
5	1661	24457	10410	2174	2412	
6	1570	13200	4962	2066	2678	
7	2134	11287	2891	1891	3435	
8	2540	8670	3617	1584	2462	
9	2994	8804	2750	2708	2318	
10	4330	10322	4668	2115	2992	

AVERAGE WEEKLY FLOW RATES CFS 1932

		1	2	3	4	5
1	4340	6184	4112	1642	6195	4261
2	9065	4954	4042	2612	4940	5904
3	13542	8710	3034	2297	10175	
4	8977	25742	2432	2072	7712	
5	8894	31642	1891	1556	8654	
6	6507	20228	1708	1426	14628	
7	7440	14514	2064	1421	16142	
8	5640	12300	3427	7481	8540	
9	5108	8147	2522	3117	6544	
10	8605	5812	1992	2831	5355	

AVERAGE WEEKLY FLOW RATES CFS 1933

		1	2	3	4	5
1	5975	12185	7318	1715	5770	3532
2	5552	13385	6098	1666	4430	3455
3	6065	14742	4960	1727	5647	
4	8855	32767	3440	2592	5535	
5	6298	29957	3094	3288	3992	
6	5990	32767	2802	2207	3878	
7	5687	27657	1915	2494	3594	
8	7350	20185	1869	7514	4874	
9	7064	11985	1746	4355	5798	
10	11877	9260	1693	3734	3828	

AVERAGE WEEKLY FLOW RATES CFS 1934

		1	2	3	4	5
1	4251	9207	6435	2660	4415	4834
2	5901	10948	4274	1827	3718	4674
3	5168	15597	3964	1446	3825	
4	6070	32271	3707	1400	4192	
5	5950	32767	5554	1486	7445	
6	4105	31300	3407	1511	5372	
7	3608	20328	1909	2950	5361	
8	3265	15200	1797	7367	7068	
9	3720	14342	1431	3761	10620	
10	13771	9148	1783	4855	4188	

AVERAGE WEEKLY FLOW RATES CFS 1935

		1	2	3	4	5
1	3958	15328	5007	2637	1984	3728
2	21524	17328	5127	2481	1725	2520
3	10268	14942	6184	2320	1650	
4	8735	11644	11114	1855	1883	
5	7597	15537	14492	1681	2003	
6	6520	18542	9331	2862	3672	
7	6937	14814	4962	3601	3438	
8	7764	12482	7751	2890	6902	
9	8678	12337	4034	2207	4757	
10	10907	7745	3274	2465	4191	

AVERAGE WEEKLY FLOW RATES CFS 1936

		1	2	3	4	5
1	4537	32767	5614	1795	2003	15488
2	5531	32767	3932	1634	4957	12950
3	9211	32767	3051	1691	4850	
4	6845	28000	2862	1560	4092	
5	5764	28171	3624	1664	5580	
6	4494	18242	2442	2224	3852	
7	4021	11725	1794	1744	2614	
8	4878	11722	2258	1753	2091	
9	4897	9150	2041	1591	3354	
10	5241	7807	1939	1862	12262	

AVERAGE WEEKLY FLOW RATES CFS 1937

		1	2	3	4	5
1	11325	7068	19400	2478	1601	9607
2	10558	12600	13385	2830	2545	7211
3	13318	8404	9681	2845	7434	
4	13357	10954	6638	2257	4860	
5	8342	16271	8685	2397	3101	
6	6454	20385	7618	2181	15075	
7	11545	20757	6090	2571	8634	
8	15447	21871	3632	2362	18178	
9	9638	17414	3285	2092	16681	
10	6100	25514	2478	2000	11085	

AVERAGE WEEKLY FLOW RATES CFS 1938

		1	2	3	4	5
1	5690	6955	8447	19928	6667	11135
2	7985	16190	5602	7832	5231	7892
3	5727	16128	4300	5724	9440	
4	15192	11387	6415	4874	7674	
5	14500	11591	4451	3915	5604	
6	14000	19314	5922	3425	5327	
7	10814	11002	5548	3775	8165	
8	8385	7782	3938	32767	7067	
9	6940	5342	6442	32767	19371	
10	7438	10041	14314	9932	25257	

AVERAGE WEEKLY FLOW RATES CFS 1939

		1	2	3	4	5
1	7314	8840	8605	2325	1721	3205
2	11251	8737	7084	2121	1522	2822
3	7144	13528	4402	2043	1574	
4	5097	19671	3832	2480	5002	
5	4832	20371	3751	2234	4687	
6	4924	32400	3621	1732	3148	
7	5534	32767	3427	1971	2307	
8	7730	20685	2192	1816	1888	
9	10090	15771	1919	1434	4511	
10	11732	8260	1749	1876	2885	

AVERAGE WEEKLY FLOW RATES CFS 1940

		1	2	3	4	5
1	1892	3584	11014	3344	1993	5608
2	1763	5315	16185	2527	1763	5162
3	3454	5580	17324	1837	1543	
4	2325	21685	9144	1785	1954	
5	1842	32767	6404	1954	5298	
6	1921	31642	4655	3834	8795	
7	3008	27185	4505	2882	7041	
8	2571	31200	4402	2437	4071	
9	2511	26757	3454	2938	3544	
10	2947	12671	3620	2400	3888	

AVERAGE WEEKLY FLOW RATES CFS 1941

		1	2	3	4	5
1	10091	5197	2775	2308	1738	2300
2	5757	5264	2820	1389	1891	4455
3	4627	8707	2402	1236	1435	
4	4504	10858	1989	1386	2542	
5	4221	12771	3285	1212	3265	
6	9311	11757	1754	1408	2356	
7	10680	6187	1482	1356	1693	
8	6905	4651	3073	1200	1711	
9	5428	5471	3122	1030	1586	
10	5177	4354	2147	1110	1898	

AVERAGE WEEKLY FLOW RATES CFS 1942

		1	2	3	4	5
1	4242	16557	6582	4254	2133	4337
2	2340	20114	4342	2570	1696	3610
3	3025	14000	3268	2852	2873	
4	4340	14914	10321	2204	4184	
5	2997	17271	10490	1732	4697	
6	2670	16457	4197	1566	4291	
7	2650	12471	4101	2231	5158	
8	3107	8590	3850	2013	9521	
9	3201	6670	2478	2278	12522	
10	12437	5617	2315	2365	6064	

AVERAGE WEEKLY FLOW RATES CFS 1943

		1	2	3	4	5
1	9015	12584	16757	3640	1634	3634
2	5000	14628	12088	5940	4832	3064
3	4360	18000	6947	6572	4264	
4	3894	11514	6241	4168	6242	
5	3651	10211	5732	2679	9477	
6	4324	13914	3784	2994	12540	
7	5034	18185	3195	3315	7547	
8	6788	20328	3032	2285	8151	
9	10345	18400	2219	1704	5592	
10	6557	20128	2697	2172	4808	

AVERAGE WEEKLY FLOW RATES CFS 1944

		1	2	3	4	5
1	2697	5011	5962	2906	3049	5545
2	2705	7510	4435	1983	2990	4392
3	2427	15191	2758	1759	4492	
4	2867	14371	3155	1630	2893	
5	3061	18971	5717	1671	2692	
6	2540	20200	29471	1748	4381	
7	2615	21685	7617	2389	3468	
8	3782	17528	4772	8914	4602	
9	3881	14442	3795	2978	7572	
10	3587	8530	2652	3202	8834	

AVERAGE WEEKLY FLOW RATES CFS 1945

		1	2	3	4	5
1	10342	15414	19300	6292	4501	6581
2	6521	31471	11840	4074	3684	6950
3	5775	27314	8335	3041	3358	
4	5364	21828	7715	2511	3125	
5	4928	13661	16614	2585	3984	
6	5098	8242	13127	3086	3944	
7	5220	13258	6625	2277	10700	
8	6227	15614	4598	3210	7342	
9	10467	16514	7558	2805	13512	
10	14471	27828	5820	5755	14900	

AVERAGE WEEKLY FLOW RATES CFS 1946

		1	2	3	4	5
1	7760	27257	12200	4401	3865	3702
2	14085	19828	16528	4304	4184	4160
3	8105	16985	13514	4194	3777	
4	6380	13628	8634	3727	3520	
5	6305	9220	5007	3491	3894	
6	6311	6770	3150	3037	4842	
7	8234	9020	2908	3152	3794	
8	7695	8771	2478	2195	3990	
9	6535	9805	2141	3074	3500	
10	19615	13428	3252	10074	4584	

AVERAGE WEEKLY FLOW RATES CFS 1947

		1	2	3	4	5
1	3981	15417	9665	3584	1242	3025
2	3652	13914	9671	2547	1103	2375
3	4268	14957	14228	2522	1134	
4	6550	16257	11071	2484	1102	
5	8804	23671	8394	2196	2089	
6	12355	17428	6124	2902	7515	
7	7528	13185	3248	2158	3330	
8	6457	17000	3098	2272	4321	
9	6684	18814	3365	1977	2672	
10	9098	10870	6715	1531	2411	

AVERAGE WEEKLY FLOW RATES CFS 1948

		1	2	3	4	5
1	2251	4342	20114	3185	1618	2805
2	2484	30057	16485	2307	1256	1992
3	2325	29514	11418	2652	1524	
4	2175	20285	13028	2105	1298	
5	2280	12157	9341	1748	2423	
6	2245	13957	6938	1502	4148	
7	2827	10451	5197	1529	6217	
8	5708	7904	6082	1390	5651	
9	4597	10577	3498	1079	3631	
10	3808	15214	3238	1137	3124	

AVERAGE WEEKLY FLOW RATES CFS 1949

		1	2	3	4	5
1	16142	7940	5295	1313	1761	3512
2	13648	7404	6748	1301	1674	4698
3	5828	16685	3707	1270	1574	
4	4910	10860	2432	1406	2526	
5	4681	11200	2059	2156	3095	
6	4557	12700	2205	1278	3055	
7	7348	11645	1431	1486	2601	
8	10538	9822	1816	1754	2962	
9	9681	8355	1726	2735	2738	
10	9138	4708	1590	1891	3231	

AVERAGE WEEKLY FLOW RATES CFS 1950

		1	2	3	4	5
1	4600	6694	5472	1088	1994	6862
2	6494	7761	5375	1125	2808	4754
3	7461	19485	8831	1160	2016	
4	5341	22685	4112	1650	2035	
5	6920	14314	2921	1762	3730	
6	5364	16500	1966	2728	2231	
7	6312	20185	1417	1687	3338	
8	4992	12000	1920	1401	19458	
9	4317	8495	1395	1214	13401	
10	4881	6157	1331	1207	15654	

AVERAGE WEEKLY FLOW RATES CFS 1951

		1	2	3	4	5
1	6034	13187	6400	6264	7494	8875
2	6152	18142	11828	3892	4981	11308
3	6702	18628	6242	4347	5685	
4	9005	32767	5114	5557	11105	
5	7284	28814	5148	4400	27528	
6	14814	19171	4344	5780	14714	
7	12885	17542	3864	4232	10552	
8	18071	12742	4144	3974	9058	
9	11857	7758	5398	3515	11080	
10	10668	7314	4481	3247	10648	

AVERAGE WEEKLY FLOW RATES CFS 1952

		1	2	3	4	5
1	13042	14314	12771	1819	2571	8297
2	10577	12714	14500	2005	1848	5720
3	11942	16457	23471	3261	1854	
4	15857	28328	9412	2900	1482	
5	16971	32767	4630	1762	1476	
6	17342	29028	3665	2672	1451	
7	10765	20257	2644	1643	2562	
8	9645	18357	2675	1895	3740	
9	8318	9964	2464	1914	3292	
10	8464	17257	1943	2735	13841	

AVERAGE WEEKLY FLOW RATES CFS 1953

		1	2	3	4	5
1	5002	28502	13800	1470	1325	8634
2	4498	24885	8075	2827	1461	6505
3	5768	32767	4610	2418	1863	
4	13472	32767	2922	1505	4124	
5	14128	23785	2312	1473	2307	
6	12145	27528	1927	1101	2340	
7	13090	19114	1555	1314	2750	
8	16000	22100	1572	1383	8335	
9	11747	18500	1815	1400	8738	
10	10527	18428	1770	1317	13557	

AVERAGE WEEKLY FLOW RATES CFS 1954

		1	2	3	4	5
1	4811	7801	24542	3448	5341	21257
2	4162	10285	15414	3161	8127	13257
3	3957	10517	14657	2700	5644	
4	5160	7840	9418	2158	8008	
5	5978	12414	6542	5261	13515	
6	5367	26428	5208	6621	7562	
7	4624	19928	5934	24555	15668	
8	11652	17342	3542	16842	14628	
9	15285	31828	2314	9998	10982	
10	14785	29528	2437	6447	11215	

AVERAGE WEEKLY FLOW RATES CFS 1955

		1	2	3	4	5
1	13314	14328	4255	1527	4000	4324
2	9638	10957	8051	1467	15012	2914
3	7092	10688	7400	5454	8420	
4	5808	16471	6818	9985	10525	
5	4735	17428	4771	6642	18757	
6	5765	19071	4534	4484	14871	
7	8877	16957	2712	3302	11375	
8	8107	15142	2512	2551	7641	
9	12457	9744	1936	2634	6508	
10	9495	6288	1835	2569	5422	

is probable that unless pollution is abated, extensive diversion out-

AVERAGE WEEKLY FLOW RATES CFS 1956

		1	2	3	4	5
1	2264	8101	8517	2221	4080	7802
2	24004	7787	13288	1866	2844	7095
3	19328	7108	14857	1729	2788	
4	8221	11061	7611	1590	2598	
5	6620	22542	3740	1502	3028	
6	7204	32767	2870	2288	2529	
7	8208	26857	2150	2238	4250	
8	7005	32767	4104	2962	5572	
9	7432	19300	6275	4818	3448	
10	9015	12771	3058	2967	6537	

AVERAGE WEEKLY FLOW RATES CFS 1957

		1	2	3	4	5
1	5187	9822	6042	1407	1159	13385
2	5270	10392	4120	1249	1142	18900
3	4730	8575	3122	1258	1957	
4	11598	10842	2216	1062	2307	
5	8395	11571	1685	876	4785	
6	6591	8185	2218	789	4585	
7	5355	7752	2627	827	5780	
8	3984	5000	2415	988	3934	
9	9698	3484	1486	1077	4042	
10	7795	4895	1231	823	12114	

AVERAGE WEEKLY FLOW RATES CFS 1958

		1	2	3	4	5
1	9751	13357	9182	3340	2322	3565
2	6900	11785	6664	2176	1733	2684
3	6948	15400	6531	1936	3125	
4	15971	23628	4187	1772	4197	
5	19128	24257	2828	1777	3892	
6	11197	29557	2292	1533	4064	
7	8577	29114	1650	1448	3477	
8	7494	24800	2935	2158	5335	
9	9205	19928	2554	2774	6354	
10	10942	14171	2195	2698	4560	

AVERAGE WEEKLY FLOW RATES CFS 1959

		1	2	3	4	5
1	2798	6817	4405	2662	4831	12657
2	2424	13127	3034	1887	2785	7915
3	2834	13442	3200	2158	14432	
4	8470	32767	2733	1371	13635	
5	4972	27428	5550	2444	9558	
6	5377	16471	4047	4297	9238	
7	4190	11240	2720	1998	8352	
8	4270	10211	2412	1965	22514	
9	3674	6828	3555	1680	13828	
10	9311	5757	4460	1887	18071	

AVERAGE WEEKLY FLOW RATES CFS 1960

		1	2	3	4	5
1	12080	6991	12347	3130	3151	5385
2	9800	7171	11821	2565	3015	4742
3	7500	7670	9757	2577	8378	
4	6692	32767	5621	2145	9494	
5	6478	32767	7102	1675	9160	
6	8090	29857	3991	1464	6361	
7	12771	20014	2957	9129	5084	
8	11171	15385	2370	7998	5557	
9	9098	11645	2795	5557	7387	
10	7888	17928	2290	4557	4488	

AVERAGE WEEKLY FLOW RATES CFS 1961

		1	2	3	4	5
1	4200	10154	7608	2661	2348	3258
2	3771	8377	9011	1774	2610	3041
3	3550	15737	5422	1551	2271	
4	3227	18642	6394	1471	1741	
5	3142	18071	4284	2428	3027	
6	3131	24785	3895	1828	3247	
7	3391	25214	2590	1742	3827	
8	5560	19000	2661	3057	5797	
9	13712	13757	3110	3848	4461	
10	13328	11424	2942	2764	3822	

AVERAGE WEEKLY FLOW RATES CFS 1962

		1	2	3	4	5
1	3551	6561	8302	1789	21242	7588
2	5651	9188	6382	2284	7428	6372
3	5658	19785	5161	2474	5347	
4	5357	32767	3847	1962	8814	
5	4344	30400	2087	1705	9907	
6	3797	14742	2281	1634	13545	
7	2987	11132	1481	1486	9420	
8	3148	15142	1552	1814	8417	
9	3635	10482	1672	1897	15201	
10	3925	6970	2168	5831	13697	

AVERAGE WEEKLY FLOW RATES CFS 1963

		1	2	3	4	5
1	5718	7012	9292	1173	1213	5290
2	5701	9154	4832	1142	1056	4482
3	5485	25657	2831	1376	1153	
4	5944	30828	2411	1302	1556	
5	5141	17285	2451	1281	9458	
6	5241	14771	1643	1588	7677	
7	4681	12568	1315	1022	5038	
8	4685	11848	1527	1109	6872	
9	4361	9680	1377	1106	7120	
10	5510	8575	1304	1599	9261	

AVERAGE WEEKLY FLOW RATES CFS 1964

		1	2	3	4	5
1	4062	15971	5592	1145	860	1870
2	3880	11465	3038	953	800	3653
3	3884	12214	2091	993	1475	
4	16928	11071	1941	1144	1188	
5	12380	17685	1654	1726	1129	
6	9011	27957	1353	920	1180	
7	6784	16857	1492	1181	1316	
8	6072	10341	1528	1011	4420	
9	5572	7024	1500	1006	2385	
10	15092	6927	1427	930	1940	

AVERAGE WEEKLY FLOW RATES CFS 1965

		1	2	3	4	5
1	3935	6440	3560	899	2435	2092
2	2942	4481	2300	723	2288	2495
3	1981	4181	2255	944	2191	
4	1761	3745	2707	995	1770	
5	1604	8204	2301	932	1471	
6	2829	14057	1564	1692	2414	
7	4090	9735	1092	1126	3720	
8	2860	8100	1421	1035	3682	
9	5482	5948	1168	1684	2897	
10	8378	4645	1022	2110	2150	

AVERAGE WEEKLY FLOW RATES CFS 1966

		1	2	3	4	5
1	3487	7890	9041	1083	1794	4441
2	2541	11017	5270	967	2705	3511
3	2285	16828	3405	1079	5677	
4	2350	9568	5335	1837	4322	
5	2224	8888	3552	1729	11298	
6	2218	9074	2103	2237	6921	
7	5997	9705	975	1566	4594	
8	5264	8338	1424	1418	4738	
9	5820	7697	1355	2524	4568	
10	10597	8962	1119	2101	5751	

AVERAGE WEEKLY FLOW RATES CFS 1967

		1	2	3	4	5
1	4194	6140	12971	3724	2424	7624
2	3738	5768	15057	3590	2504	5692
3	3314	8815	7334	2775	3165	
4	4058	28728	6177	2598	3181	
5	5112	22685	6917	2507	3678	
6	4070	24471	6952	1732	3010	
7	3555	20500	5898	1938	3874	
8	3525	15757	4241	1469	5132	
9	3171	17042	3802	1573	5651	
10	3198	16685	3621	3275	9494	